From Daya Bay to Jiangmen

Wei Wang / 王為, Sun Yat-Sen University
(on behalf of both Daya Bay and JUNO)

NuFACT'15, Rio de Janeiro, Aug 13, 2014

- *Daya Bay and Its latest (oscillation) results*
- *Resolving Neutrino MH using Reactors*
- *The Jiangmen Underground Neutrino Observatory*
- *The current status and expected performance*
- *Summary and conclusion*

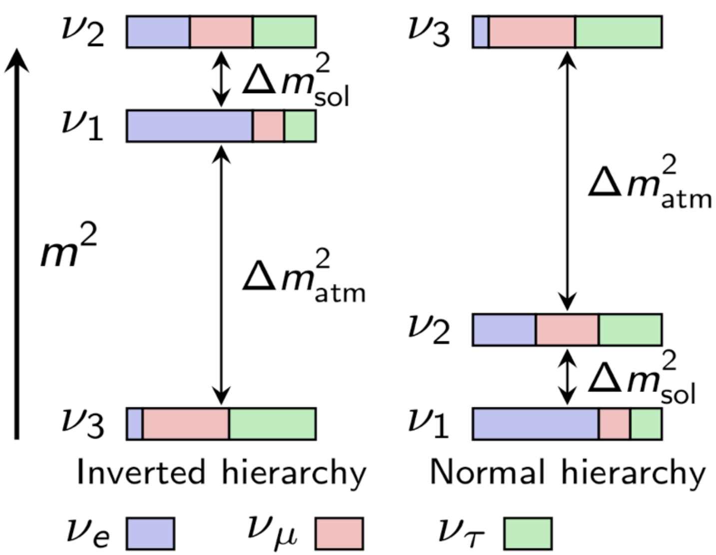
Picture of the Field for a Decade (2002-2012)

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

?

Atmospheric Sector:
SK, K2K, T2K, **MINOS**, etc

Solar Sector:
SNO, SK, KamLAND etc



Best by MINOS

Best by KamLAND

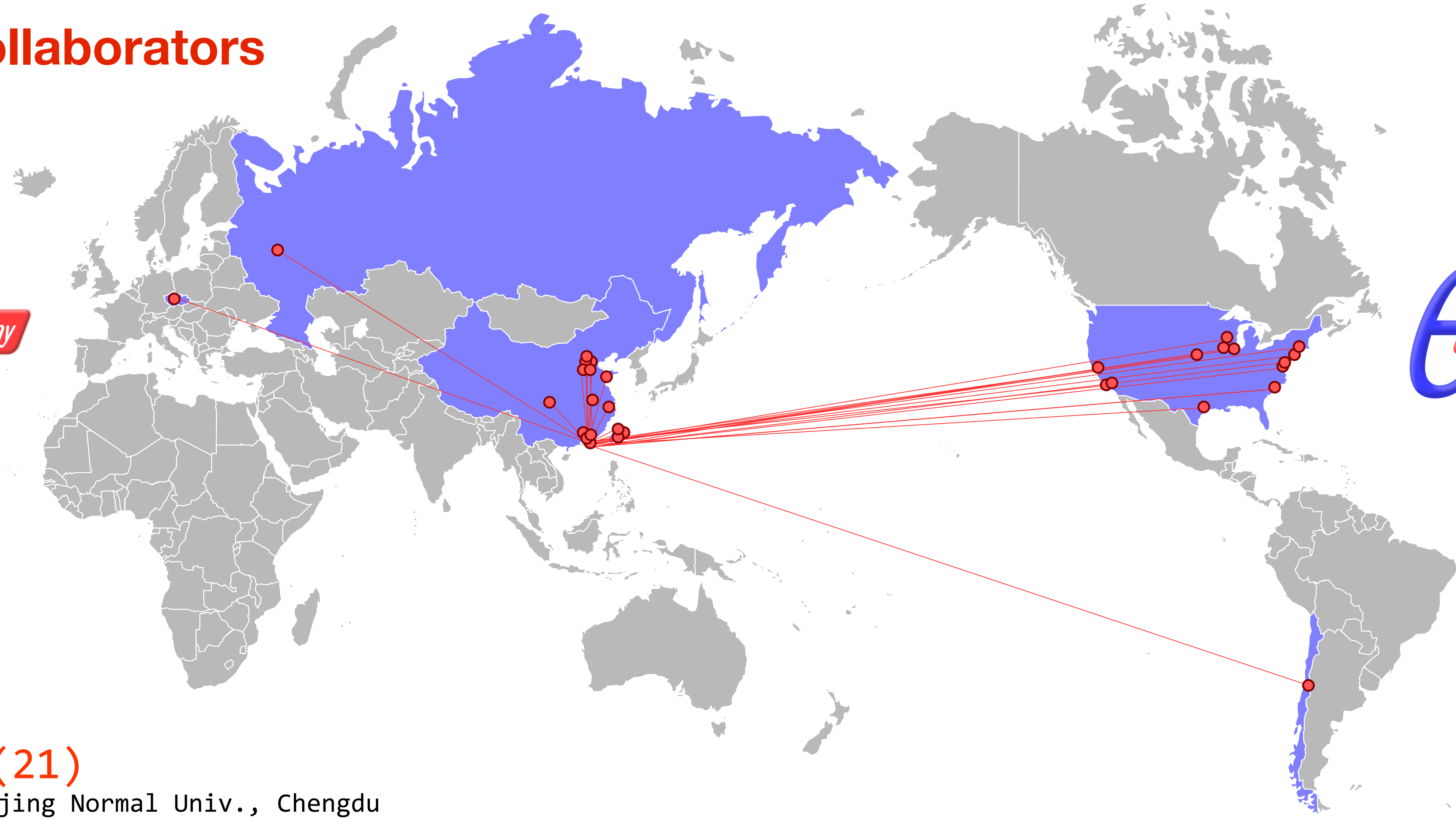
Invert ? Normal

States m_1 and m_2 are differentiated by solar neutrino data (MSW effect)

Glashow's Request of θ_{13} in 2003
(Photo by Kam-Biu Luk)

The Daya Bay Collaboration

~230 collaborators



Asia (21)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG,CIAE, Dongguan Univ. of Tech., Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xi'an Jiaotong Univ., Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (17)

BNL, LBNL, Iowa State Univ., RPI, Illinois Inst. Tech., Princeton, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin, William & Mary, Virginia Tech., Univ. of Illinois-Urbana-Champaign, Siena, Temple Univ, Yale

Europe (2)

JINR, Dubna, Russia; Charles University, Czech Republic

South America (1)

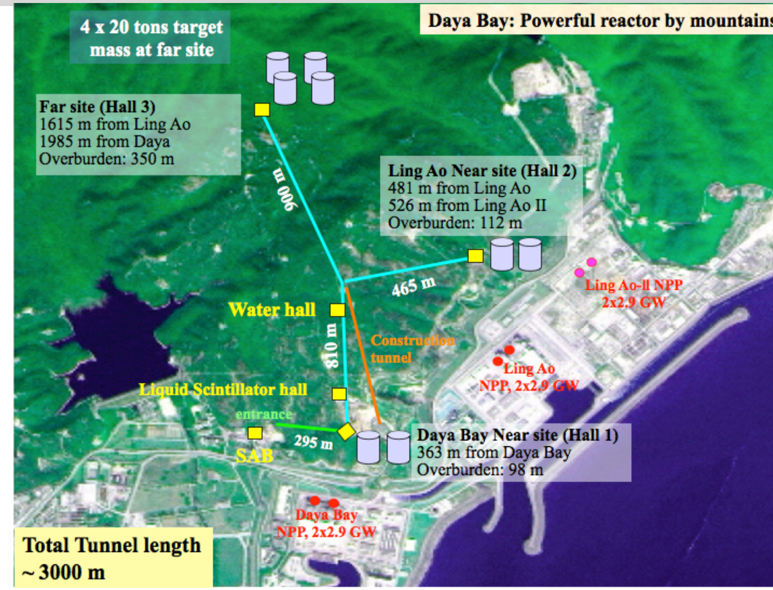
Catholic Univ. of Chile

Measuring θ13 using Reactors at Daya Bay

- Two practical ways to measure θ_{13}

$$P_{\nu_\alpha \to \nu_\beta} = 1 - 4\sum_{i<j} |V_{\alpha j}|^2 |V_{\beta i}|^2 \sin^2 \frac{\Delta m^2_{ji} L}{4E}$$

  - **Appearance experiments $\nu_\mu \to \nu_e$** depend on 3 unknown parameters θ_{13}, δ_{CP} and mass hierarchy
  - **Short-baseline reactor experiments $\nu_e \to \nu_e$** depend on 2 unknown parameters θ_{13} and mass hierarchy, with mass hierarchy has little effect



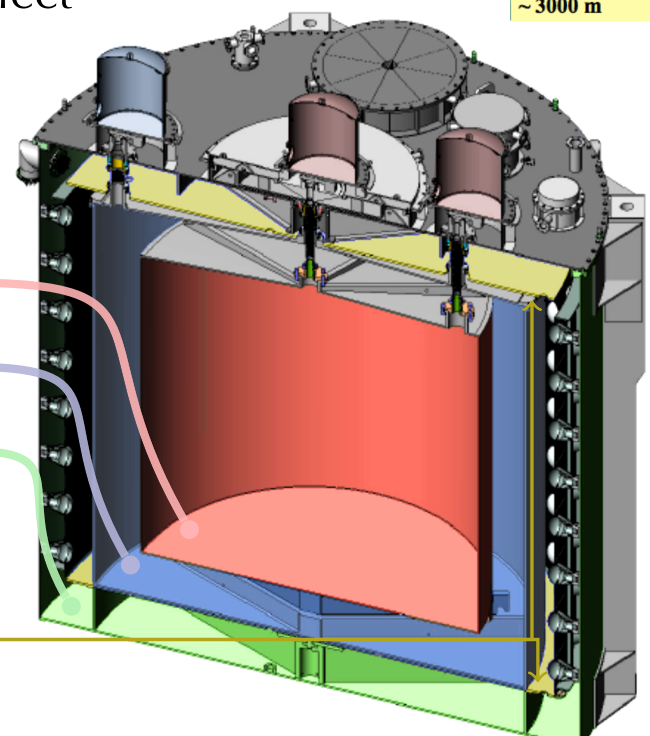
3 zone cylindrical vessels

	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

192 8 inch PMTs in each detector

Top and bottom reflectors increase light yield and flatten detector response

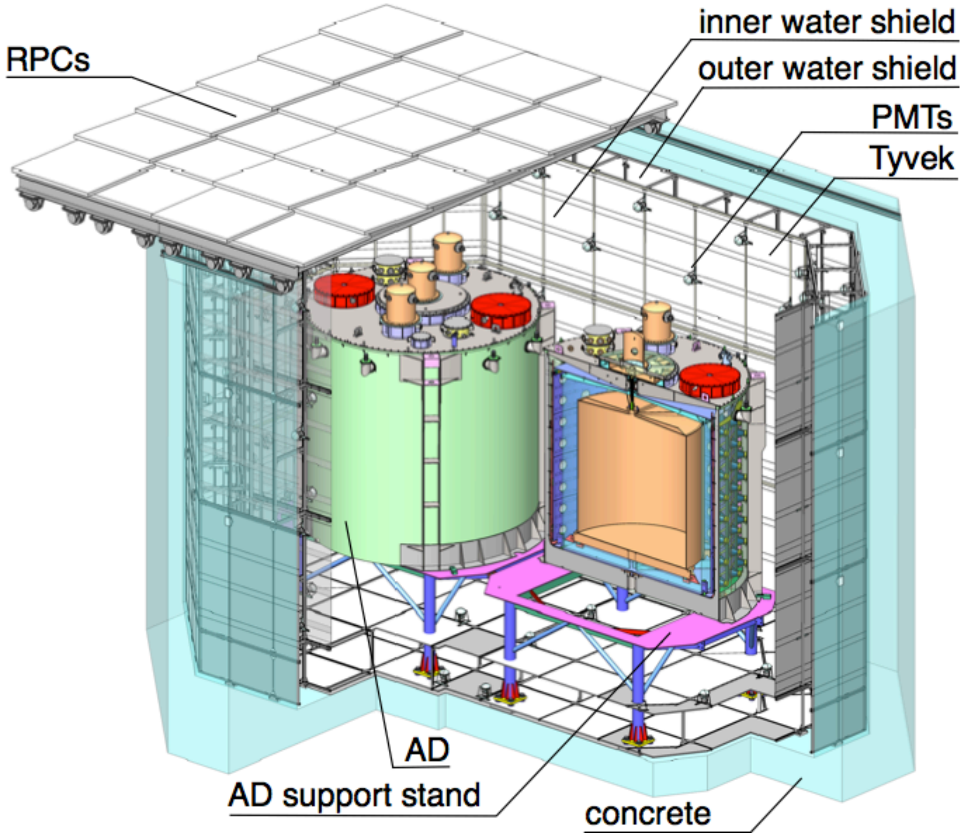
$(\frac{7.5}{\sqrt{E}} + 0.9)\%$ energy resolution



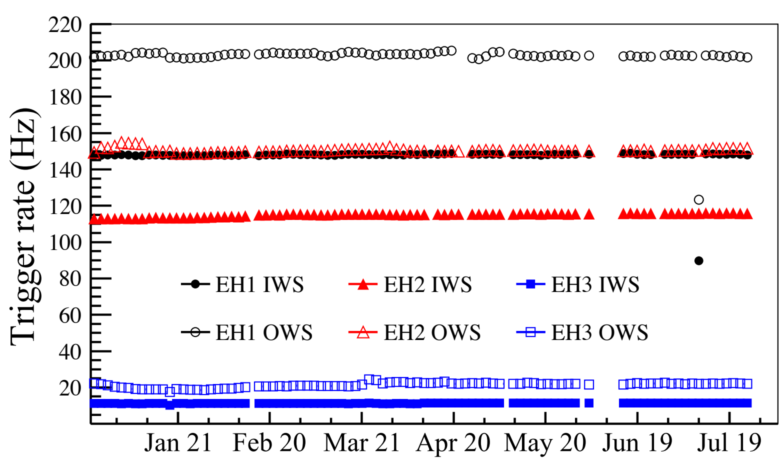
Important lessons learned from past reactor experiments:

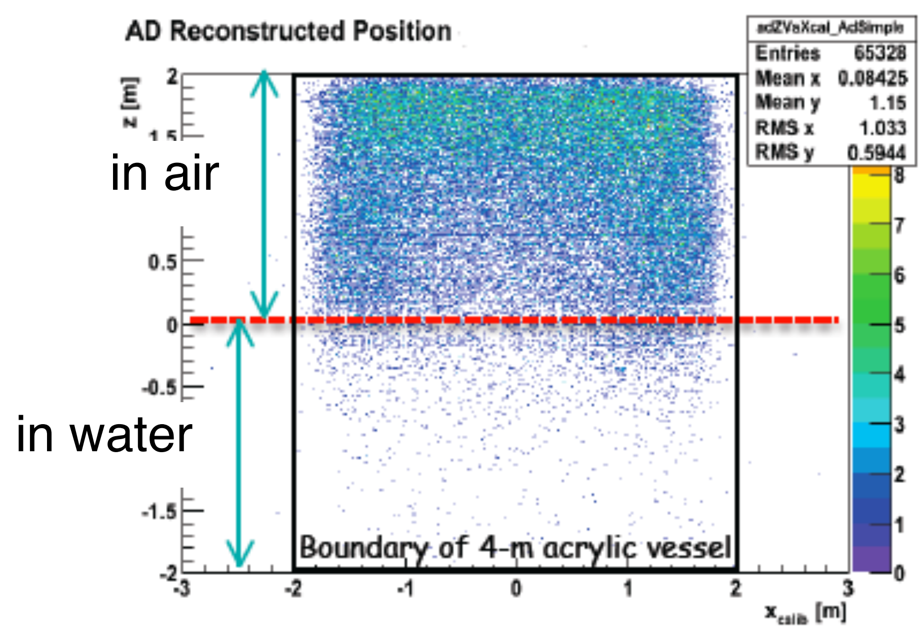
- Near-far reactor flux uncertainty **cancellation.** (First proposed for Kr2Det in 2000)
- 2 versus many: functionally **"identical"** detectors
  - ✦ And 8 is the lucky number of Daya Bay due to the layout of the reactors

Veto/Reduce Cosmic/Environmental Backgrounds



- ~100m-350m overburdens for 3 sites
- Two independent active muon veto systems: RPC; Water Cherenkov is separated into inner (IWS) and outer (OWS) ones to improve the muon efficiency
- Water Cherenkov detectors also shields the environmental gamma radiations
  - >2.5 m thick water in each direction





Daya Bay Progresses since Summer 2011

A. Two-detector data taking checking "identical" detectors, 9/23/11 – 12/23/11, [90 days]

- Side-by-side comparison of 2 detectors, *NIM A **685**, 78-97 (2012)*

B. Partial Daya Bay six-detector data taking 12/24/11 – 7/28/12, [217 days]

- The discovery, θ_{13}, *PRL. **108**, 171803 (2012)*, [55 days]
- θ_{13}, *CPC **37**, 011001 (2013)*, [139 days]
- The 1st shape analysis, θ_{13} & Δm^2_{ee}, *PRL. **112**, 061801 (2014)*, [217 days]
- An independent θ_{13} using n-captures on H, *PRD**90** (2014) 7, 071101* [217 days]
- A light sterile neutrino searches, *PRL**113**, 141802(2014)* [217 days]
- Daya Bay reactor antineutrino flux analysis (results official, the paper finalizing)

C. Shutdown, 8-detector completion and special calibrations

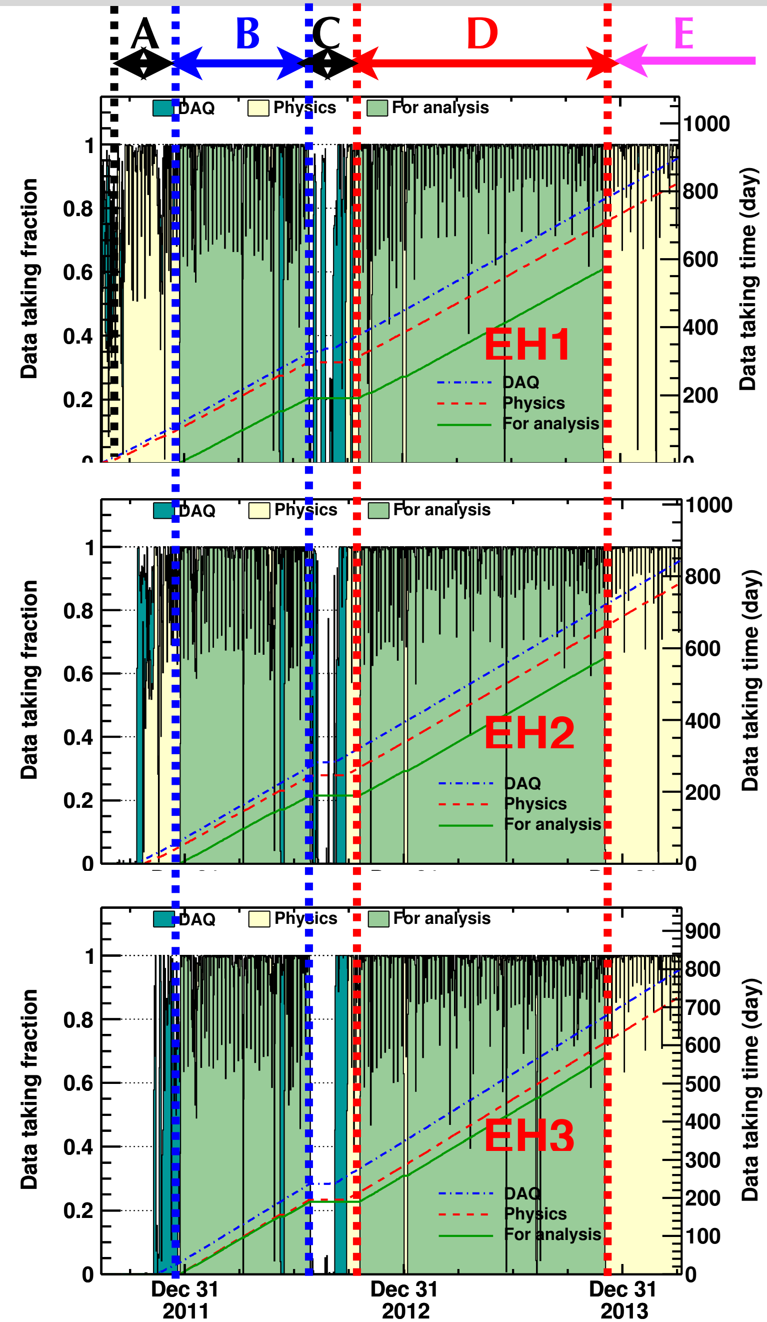
- Calibration with the manual calibration system, special sources, and reconfiguration of Am-C sources in far site detectors

D. Complete Daya Bay 8-detector data taking from 10/19/12-11/28/2013 [404 days]

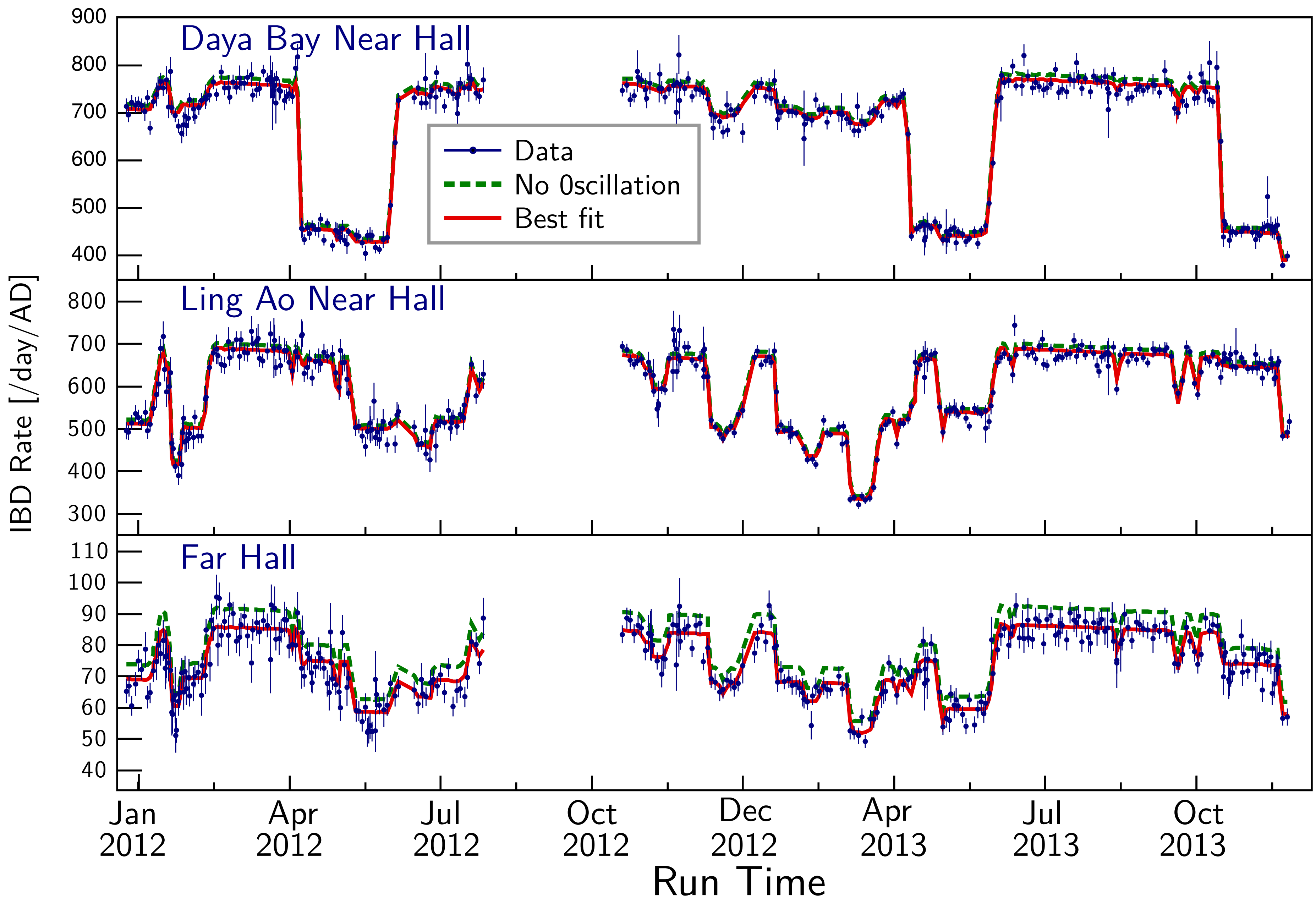
E. Being analyzed

The latest Daya Bay results based on Periods B and D, 621 days of data,

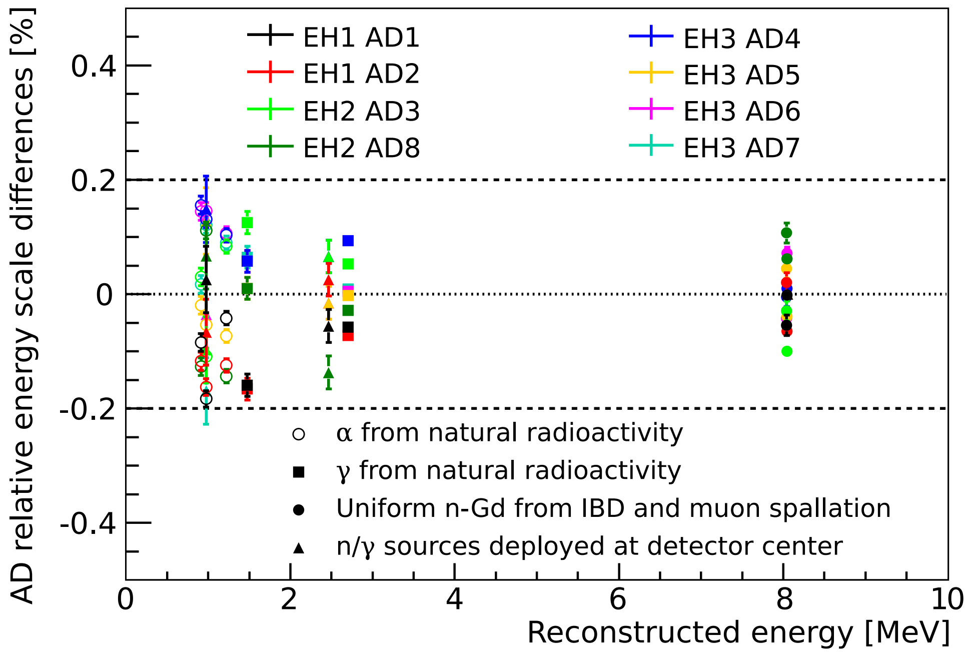
- An updated detector energy model
- Improved relative energy scale understanding
- Crosschecks of multiple analysis methods
- The most precise θ_{13} and the most precise Δm^2_{ee}, ***arXiv:1505.03456*, *to be published on PRL***



The Daya Bay Event Rates at Different Sites

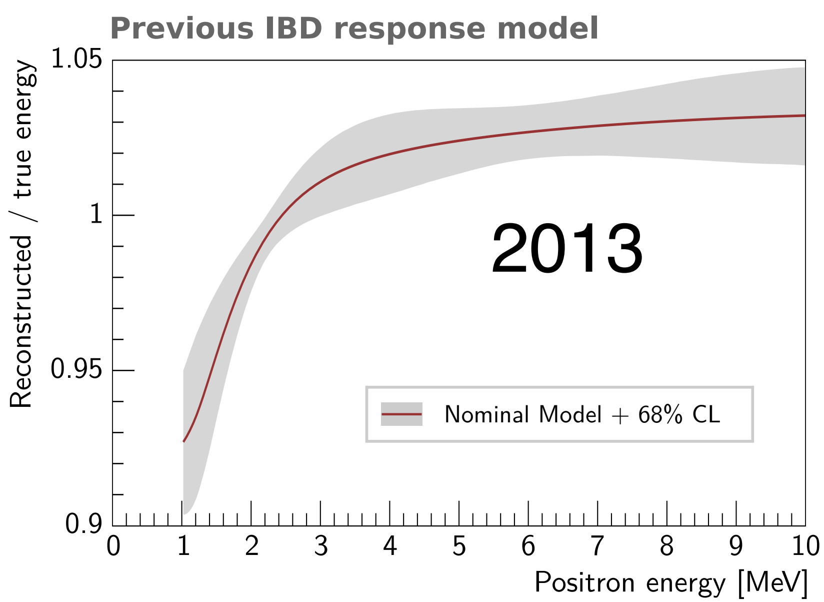


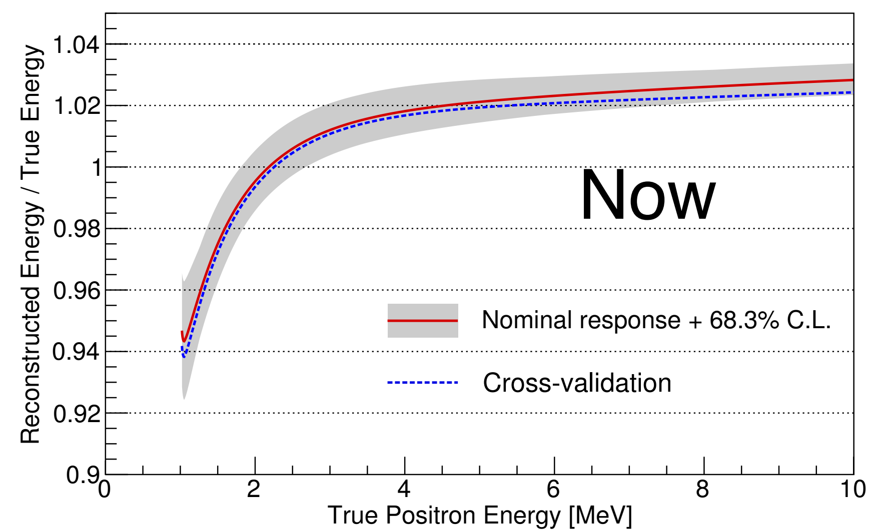
Improvements in Understanding the Energy Responses (2013-Now)



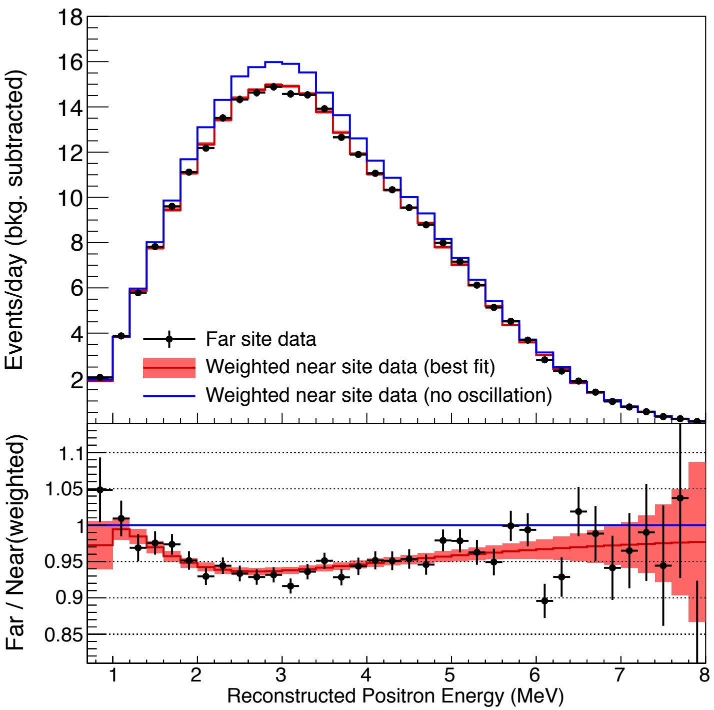
- We are able to improve the relative energy scale uncertainty between different detectors from 0.35% to 0.2%,
    - As the largest contributor to the theta13 uncertainty, this is a big improvement to its precision

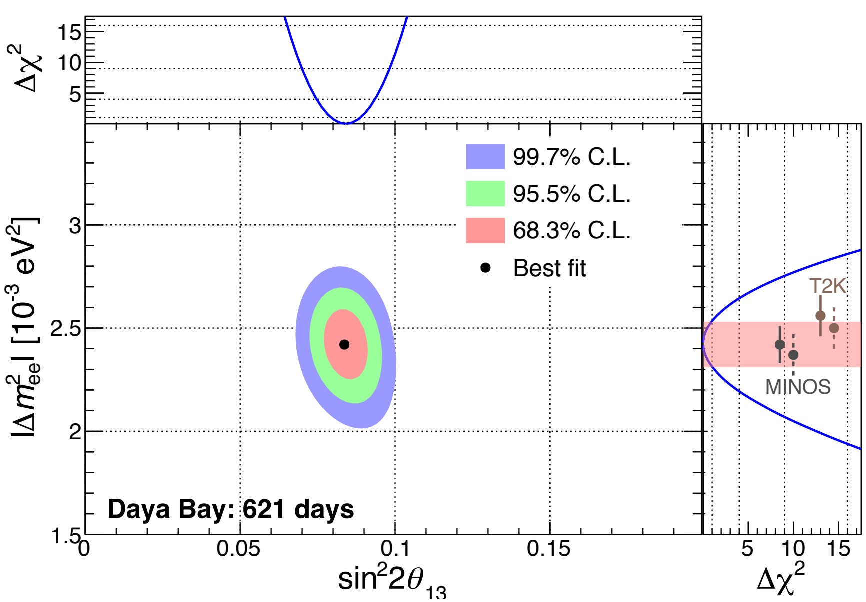
More details on the energy response understanding in Y. Gornushkin's poster and his parallel talk on Friday





The Most Precise θ_{13} Measurement by Daya Bay





- The latest published analysis has taken a method which predicts the far expectation based on the near observation, considering the oscillation effects

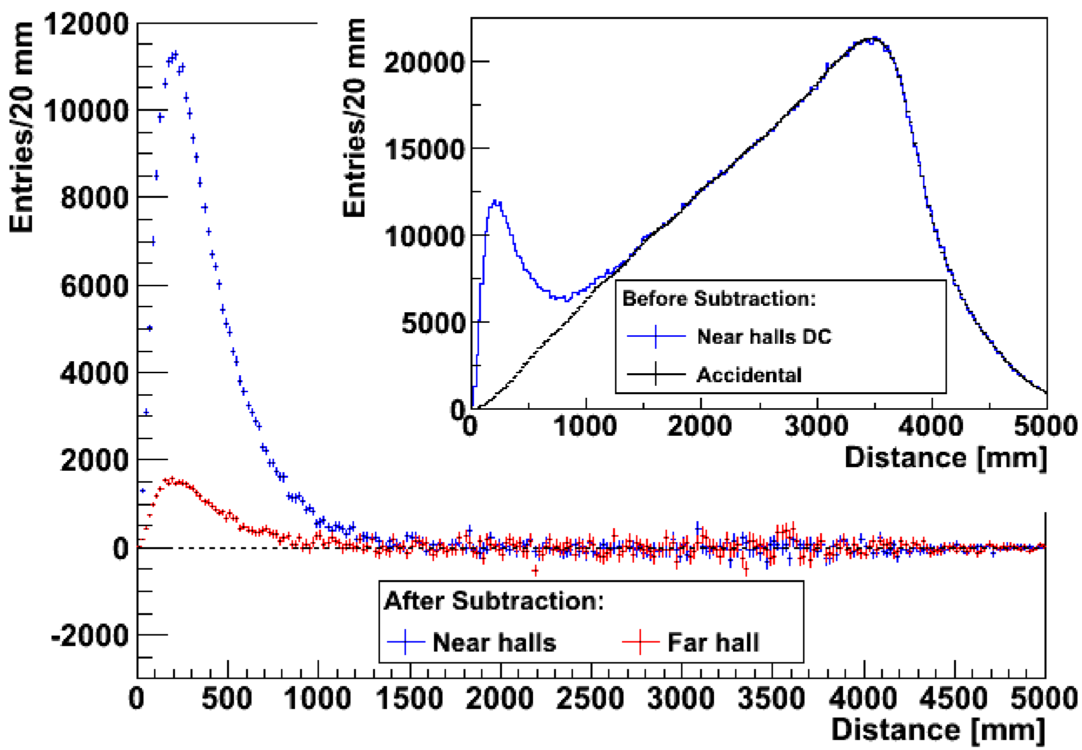
$$\chi^2 = \sum_{i,j} (N^{\mathrm{f}}_j - w_j \cdot N^{\mathrm{n}}_j)(V^{-1})_{ij}(N^{\mathrm{f}}_i - w_i \cdot N^{\mathrm{n}}_i)$$

  - The weighting factor $w_{i,j}$ considers the oscillation effects at different near detectors; the covariance matrix V considers both statistical and systematic uncertainties and the oscillation effects at different points in the phase space the minimization is carried out.

$$\begin{cases} \sin^2 2\theta_{13} = 0.084 \pm 0.005 \\ |\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} eV^2 \end{cases}$$

*to appear on **Phys. Rev. Lett., arXiv:1505.03456***

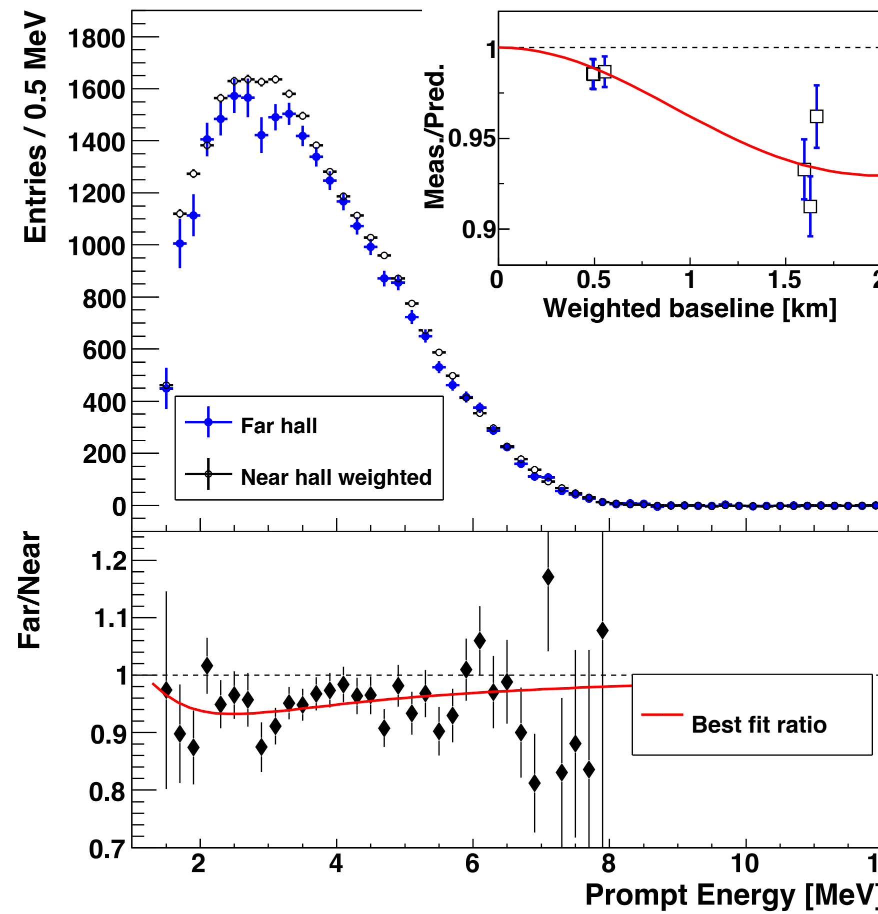
θ_{13} Oscillation Analysis using Captures on H



- Daya Bay detectors are effectively 2-zone detectors for IBD detection like KamLAND — additional ~65% IBDs.
- nH IBD events: lower delayed energy & longer correlation window, S/N~1 initially.

➡ From the systematic perspective, nH samples are largely independent of nGd samples

➡ nH based analysis shows independently convincing θ_{13} driven oscillation

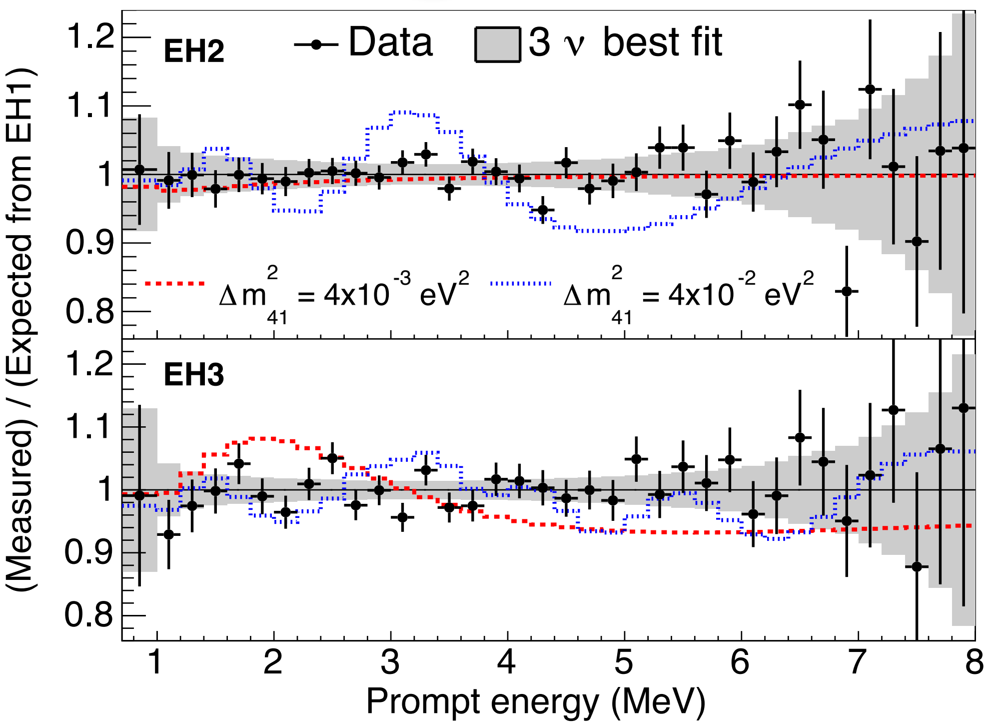


$\sin^2 2\theta_{13} = 0.083 \pm 0.018$

Phys. Rev. D90, 071101(R) (2014)

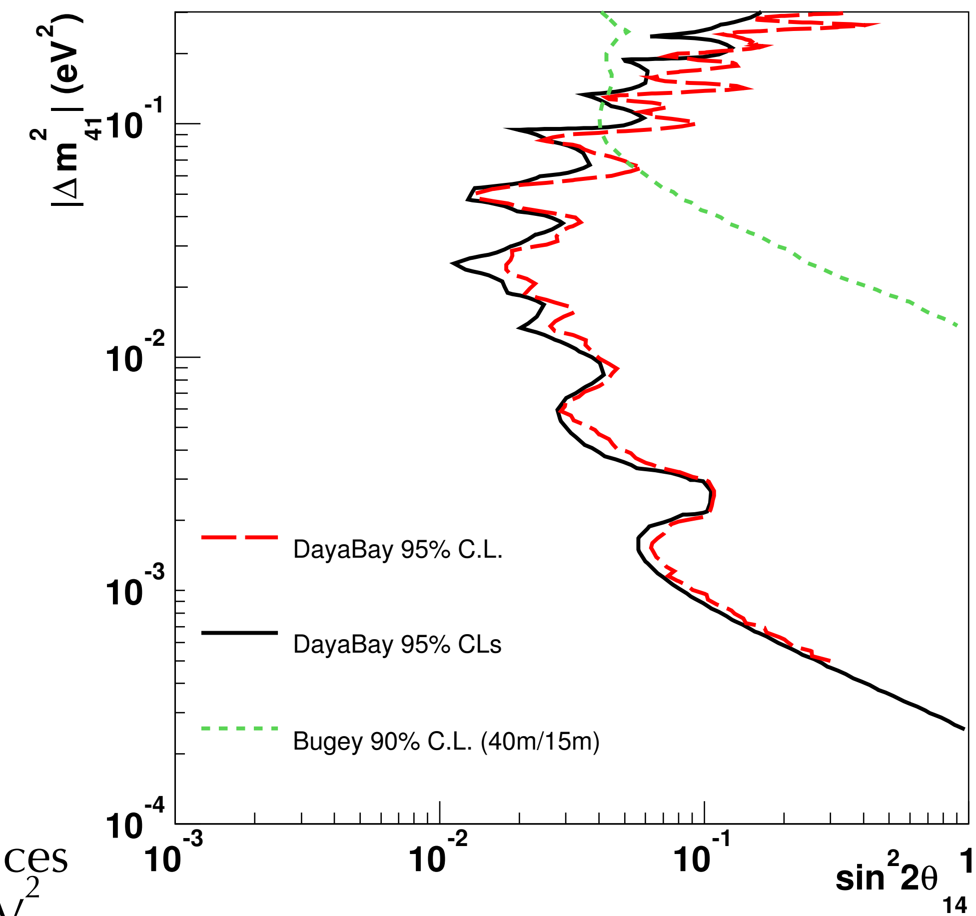
A Unique Opportunity for Sterile Neutrino Searches

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$



dashed curves assumes $\sin^2 2\theta_{14} = 0.1$

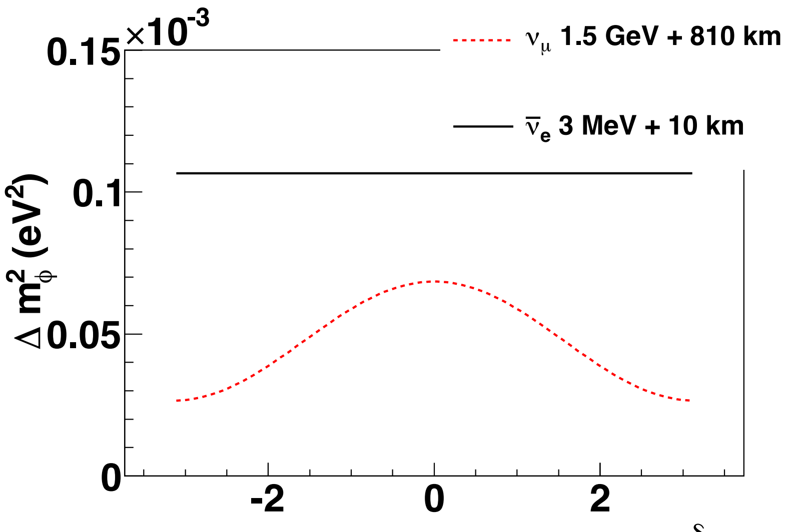
- Daya Bay baselines >350m ⇒ not as sensitive to mass-squared splittings greater than or around 1eV^2



Phys. Rev. Lett. 113, 141802 (2014)

- Daya Bay has multiple baselines whose differences enable searches in the range of Δm^2~0.01-0.1eV^2, independent of reactor flux models

Why is the Δm^2_{ee} Measurement Interesting?



Qian et al, PRD87(2013)3, 033005

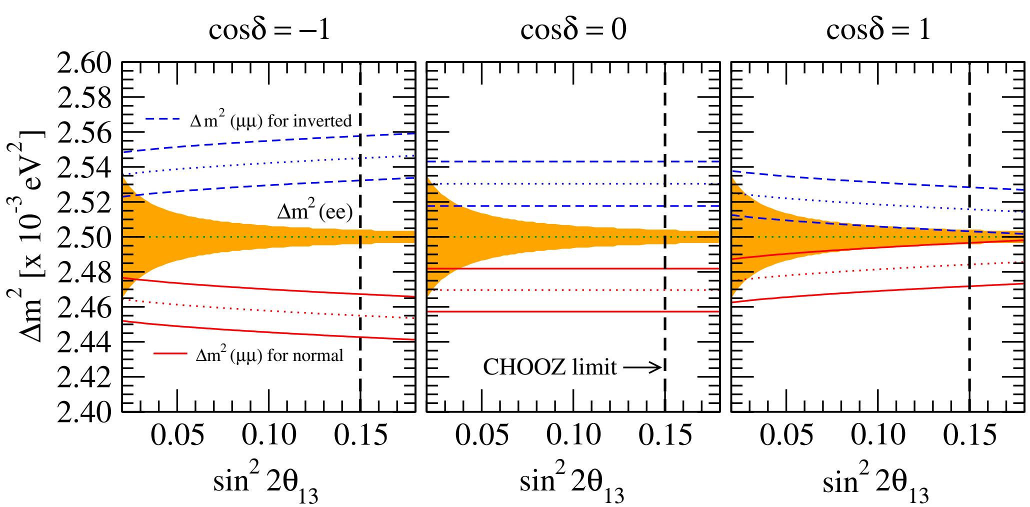
FIG. 6: The dependence of effective mass-squared difference $\Delta m^2_{ee\phi}$ (solid line) and $\Delta m^2_{\mu\mu\phi}$ (dotted line) w.r.t. the value of δ_{CP} for $\bar{\nu}_e$ and ν_μ disappearance measurements, respectively.

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$= 1 - 2s^2_{13}c^2_{13} - 4c^4_{13}s^2_{12}c^2_{12}\sin^2\Delta_{21} + 2s^2_{13}c^2_{13}\sqrt{1 - 4s^2_{12}c^2_{12}\sin^2\Delta_{21}}\cos(2\Delta_{32} \pm \phi)$$

$$P_{\nu_\mu \to \nu_\mu} = 1 - P^\mu_{21} - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\frac{(\Delta m^2_{32} \pm \phi)L}{4E}$$

Because it could, potentially, tell MH!

But it is too hard of a job from this approach.



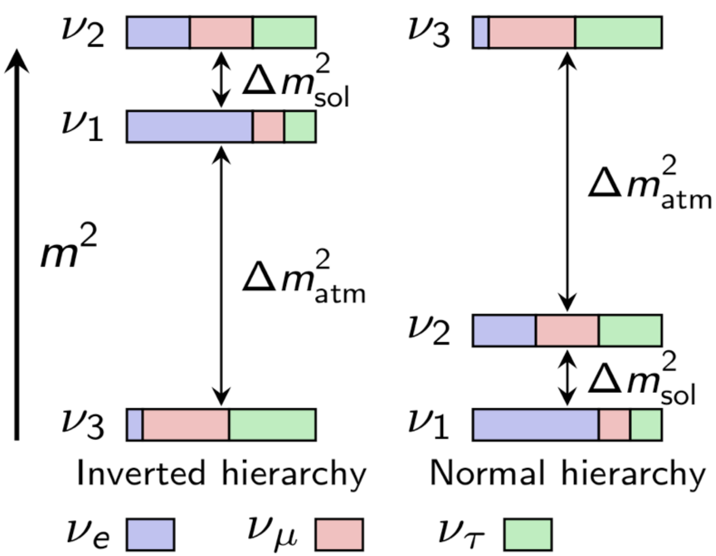
Minakata et al PRD74(2006), 053008

TABLE II: Simple fitting for mass splitting Δm^2_{32} and Δm^2_{31} using Eqs. (11), (12), (16), and (19) in NH (or (20) in IH) as constraints. The corresponding 2-tailed p-values increase from that in Table I. Here the slight preference for normal hierarchy remains.

	Fit in normal hierarchy	Fit in inverted hierarchy
Δm^2_{32}	$(2.46 \pm 0.07) \times 10^{-3}$ eV^2	$-(2.51 \pm 0.07) \times 10^{-3}$ eV^2
Δm^2_{31}	$(2.53 \pm 0.07) \times 10^{-3}$ eV^2	$-(2.44 \pm 0.07) \times 10^{-3}$ eV^2
χ^2/DoF	0.96/2	1.21/2
p-value	62%	55%

Zhang&Ma, arXiv:1310.4443

Known θ13 Enables Neutrino Mass Hierarchy at Reactors



- How to resolve neutrino mass hierarchy using reactor neutrinos
  - KamLAND (long-baseline) measures the solar sector parameters
  - Short-baseline reactor neutrino experiments designed to utilize the oscillation of atmospheric scale
  - ✓ Both scales can be studied by observing the spectrum of reactor neutrino flux

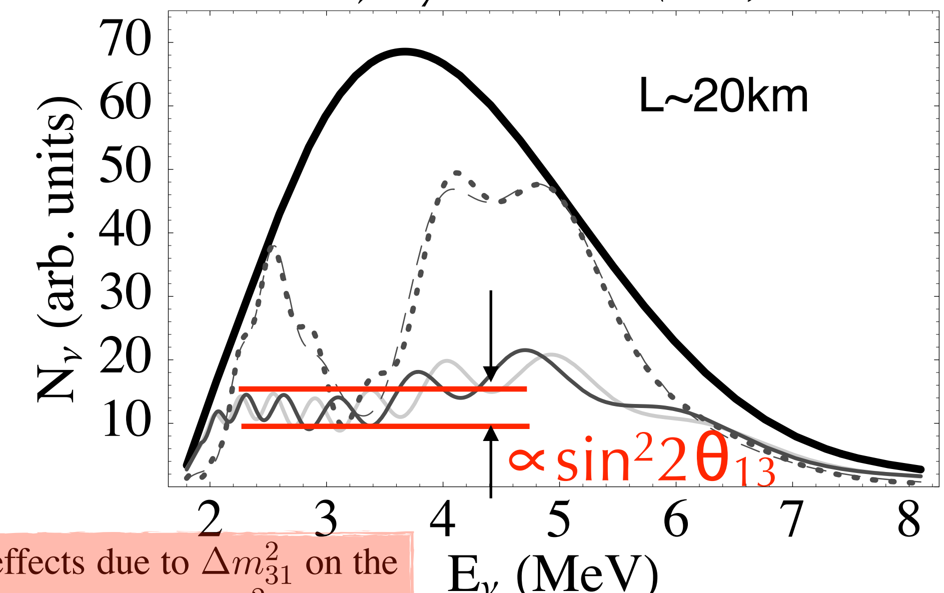
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}$$

$$- \boxed{\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})}$$

✓ Mass hierarchy is reflected in the spectrum

✓ Signal independent of the unknown CP phase

Petcov&Piai, Phys. Lett. B533 (2002) 94-106

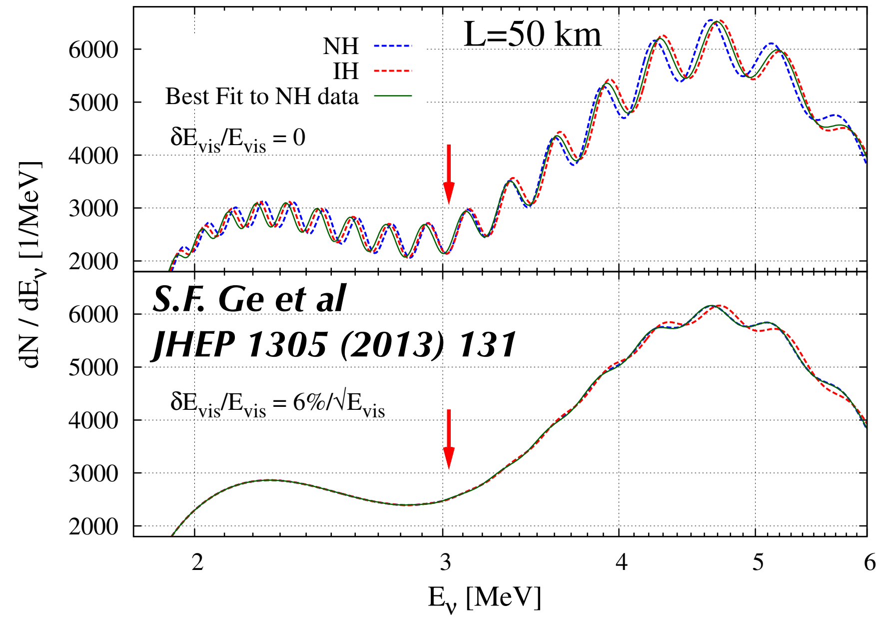


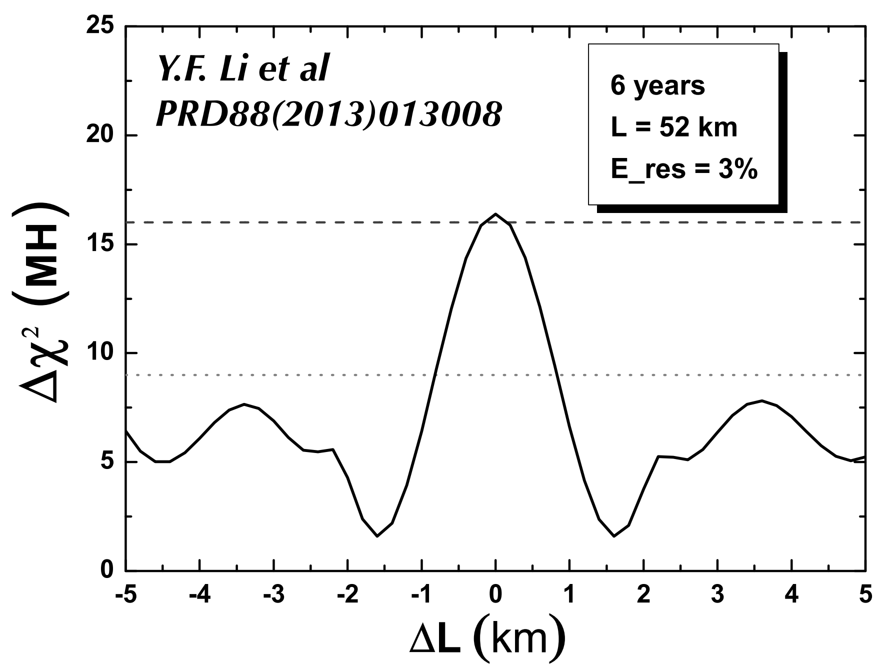
- the value of $\sin^2\theta$, which controls the magnitude of the sub-leading effects due to Δm^2_{31} on the $\Delta m^2_{\odot}$−driven oscillations: the effect of interest vanishes in the decoupling limit of $\sin^2\theta \to 0$;

Realization&Plausibility: L. Zhan et al, PRD.78.111103; J. Learned et al PRD.78.071302

Challenges in Resolving MH using Reactor Sources

- Energy resolution: ~3%/sqrt(E)
  - Bad resolution leads to smeared spectrum and the MH signal practically disappears
- Energy scale uncertainty: <1%
  - Bad control of energy scale could lead to no answer, or even worse, a wrong answer
- Statistics (who doesn't like it?)
  - ~36GW thermal power, a 20kt detector plus precise muon tracking to get the best statistics
- Reactor distribution: <~0.5km
  - If too spread out, the signal could go away due to cancellation of different baselines
  - JUNO baseline differences are within half kilometer.





Jiangmen Underground Neutrino Observatory

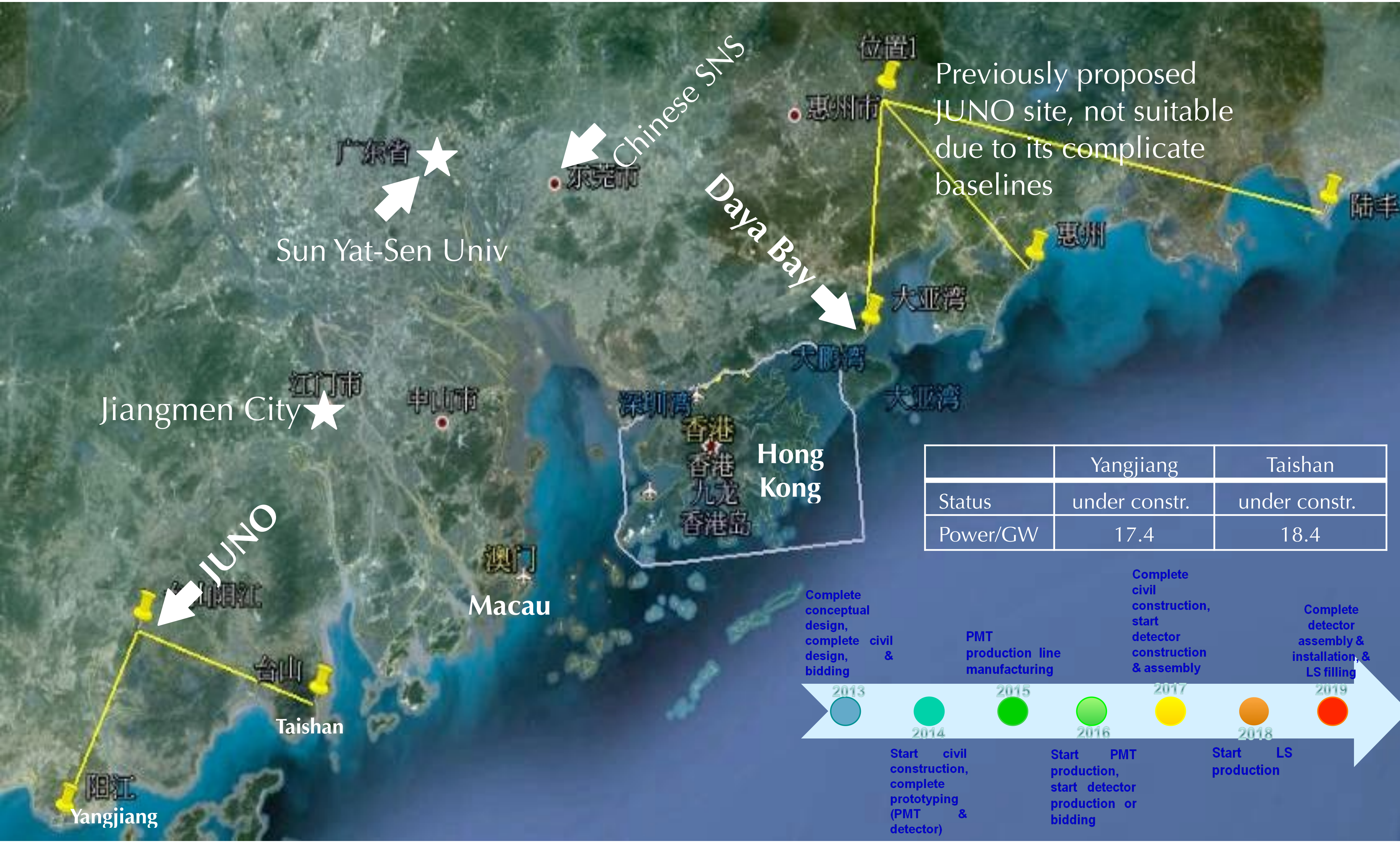
China to build a huge underground neutrino experiment

Mar 24, 2014 5 comments

Test site for the Jiangmen Underground Neutrino Observatory

"Work has started on a huge underground neutrino lab in China. The $330m Jiangmen Underground Neutrino Observatory (JUNO) is being built in Kaiping City, Guangdong Province, in the south of the country around 150 km west of Hong Kong. When complete in 2020, JUNO is expected to run for more than 20 years, studying the relationship between the three types of neutrino: electron, muon and tau."

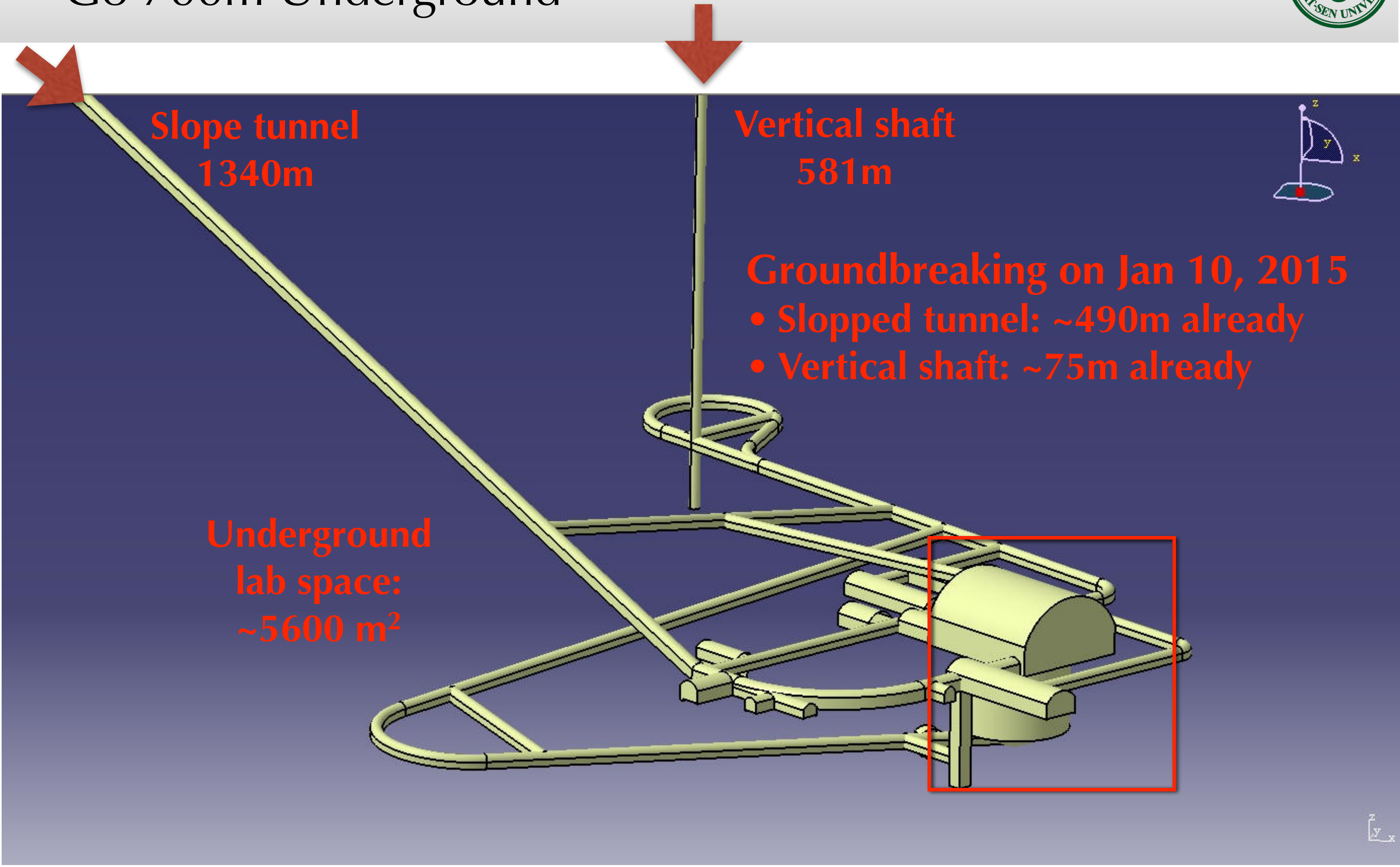
A Medium-Baseline Reactor Neutrino Experiment



	Yangjiang	Taishan
Status	under constr.	under constr.
Power/GW	17.4	18.4

Surface Facilities: Look into the Near Future……

Go 700m Underground



Groundbreaking on Jan 10, 2015

- Slopped tunnel: ~490m already
- Vertical shaft: ~75m already

Slope Tunnel Progress

As of July 6, digging 422 meters (of 1340.6 meters)

Roughly 4 meters/day

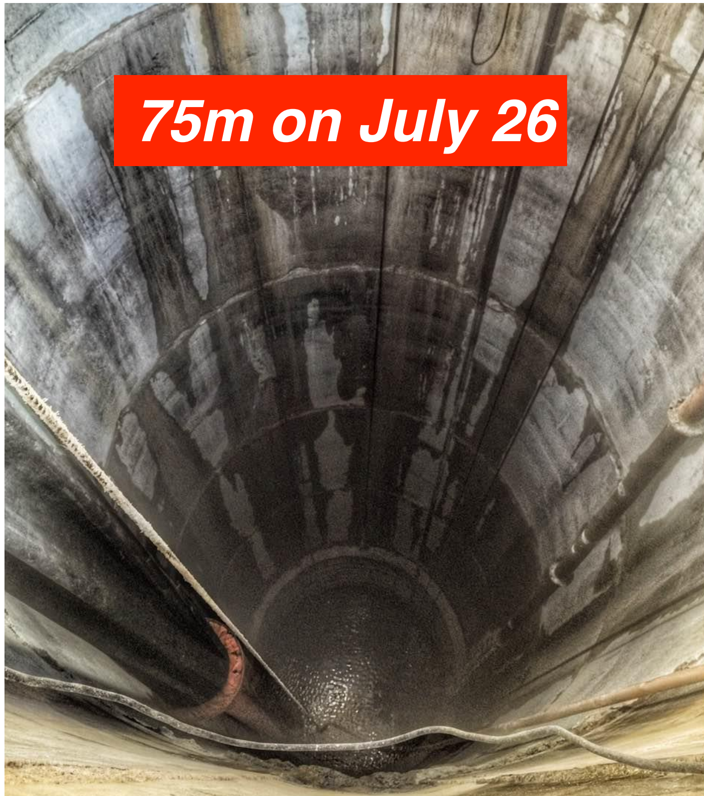
491m on July 26

Rock type-III

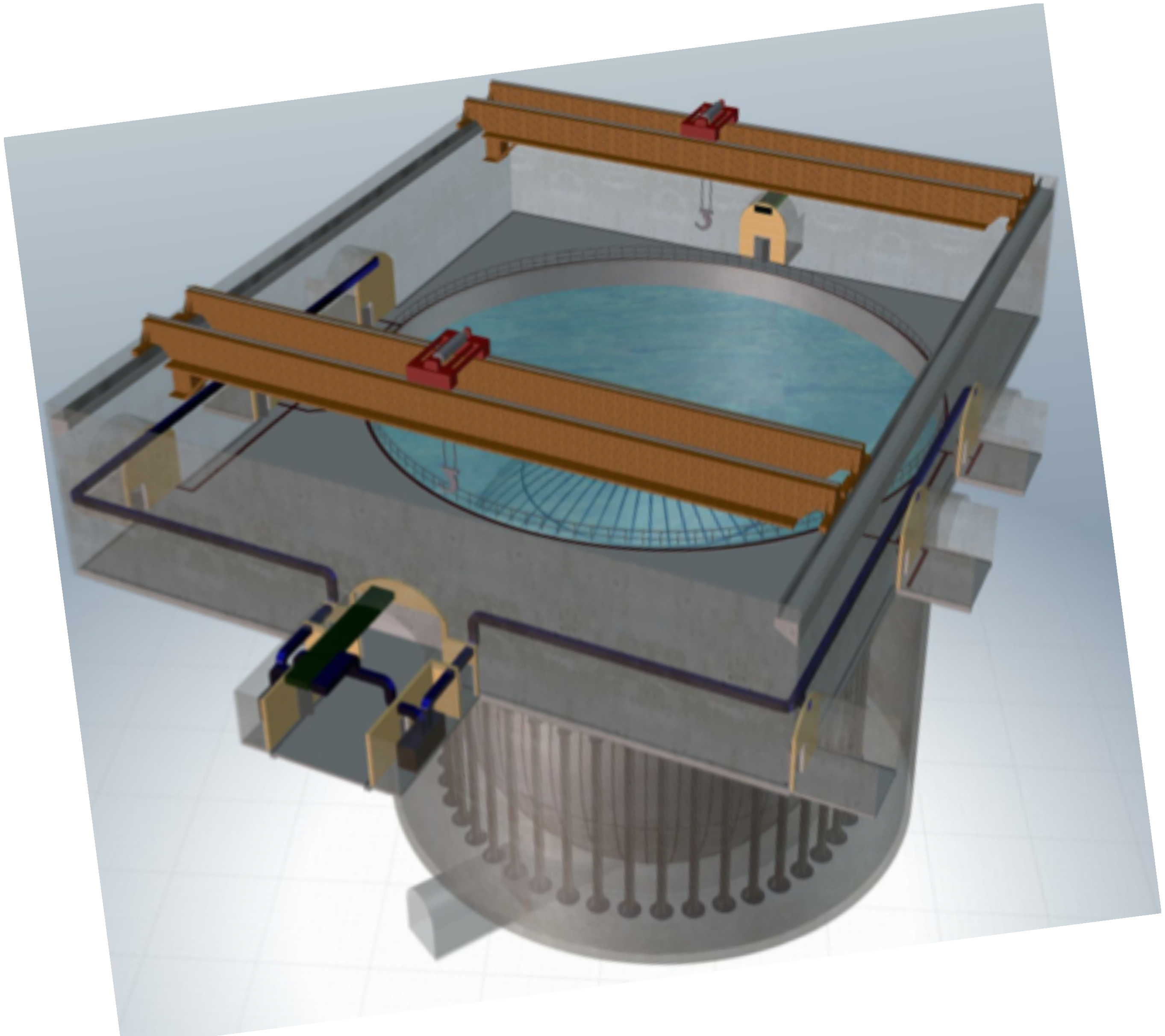
Little underground water leakage

Slope Tunnel

Vertical Shaft Groundbreaking and Progress

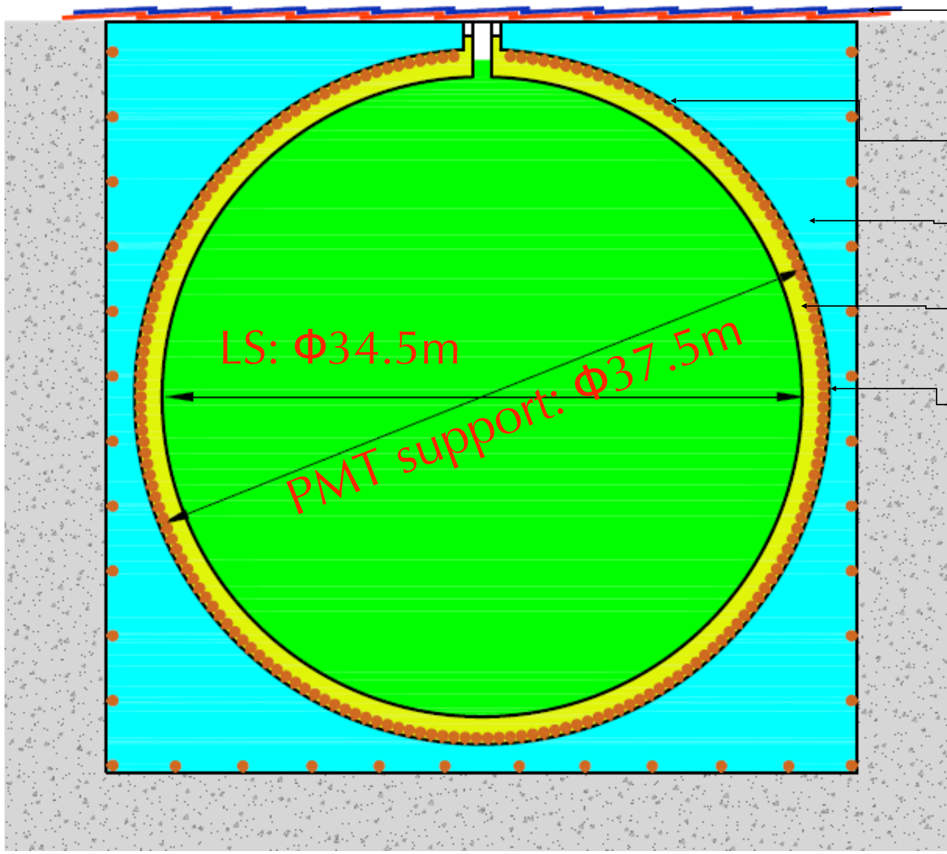


The Underground Detector System of JUNO



- A 55x48x27 m^3 main experimental hall and other halls&tunnels for electronics, LS, water, power, refuge and other facility rooms.
- A 20kt spherical liquid scintillator detector
- The muon veto system combines a cylindrical water Cherenkov detector (~42.5m in diameter and depth) and the OPERA calorimeters on the top to provide tracking information

A Conceptual Design of the Detector is Formed



$$\frac{\Delta E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

Energy leakage & non-uniformity — Photon statistics — Noise (~background)

To reach ~3%/√E energy resolution,

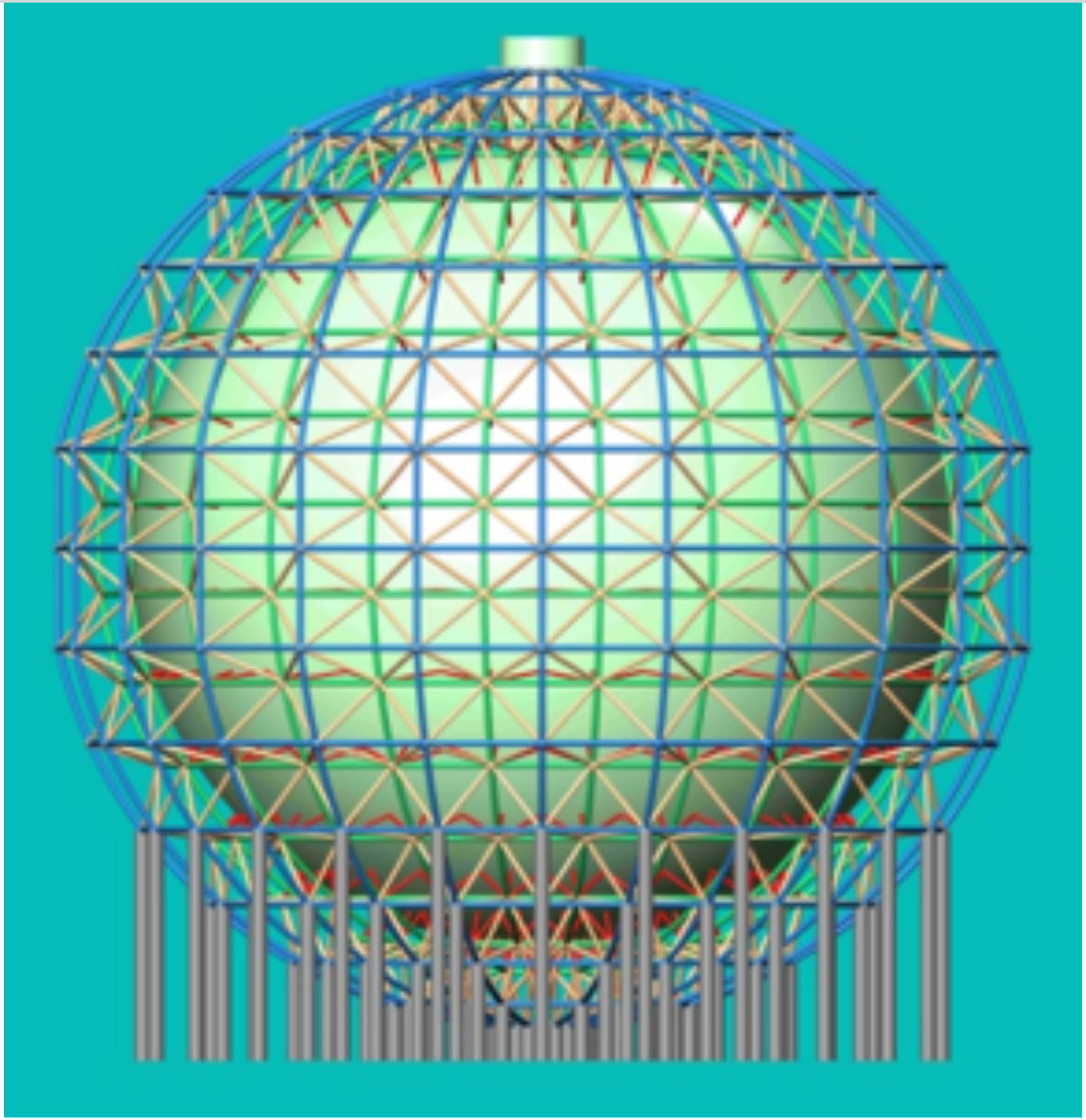
- Obtain as many photons as possible → high light yield scintillator, high photocathode coverage, and high detection efficiency PMTs
- Keep the detector as uniform as possible → a spherical detector
- Keep the noise as low as possible → clean materials and quiet PMTs

The Detector Performance Goals

	Daya Bay	BOREXINO	KamLAND	JUNO
Target Mass	20t	~300t	**~1kt**	**~20kt**
PE Collection	~160 PE/MeV	**~500 PE/MeV**	~250 PE/MeV	**~1200 PE/MeV**
Photocathode Coverage	~12%	**~34%**	**~34%**	**~80%**
Energy Resolution	~7.5%/√E	**~5%/√E**	~6%/√E	**3%/√E**
Energy Calibration	~1.5%	**~1%**	~2%	**<1%**

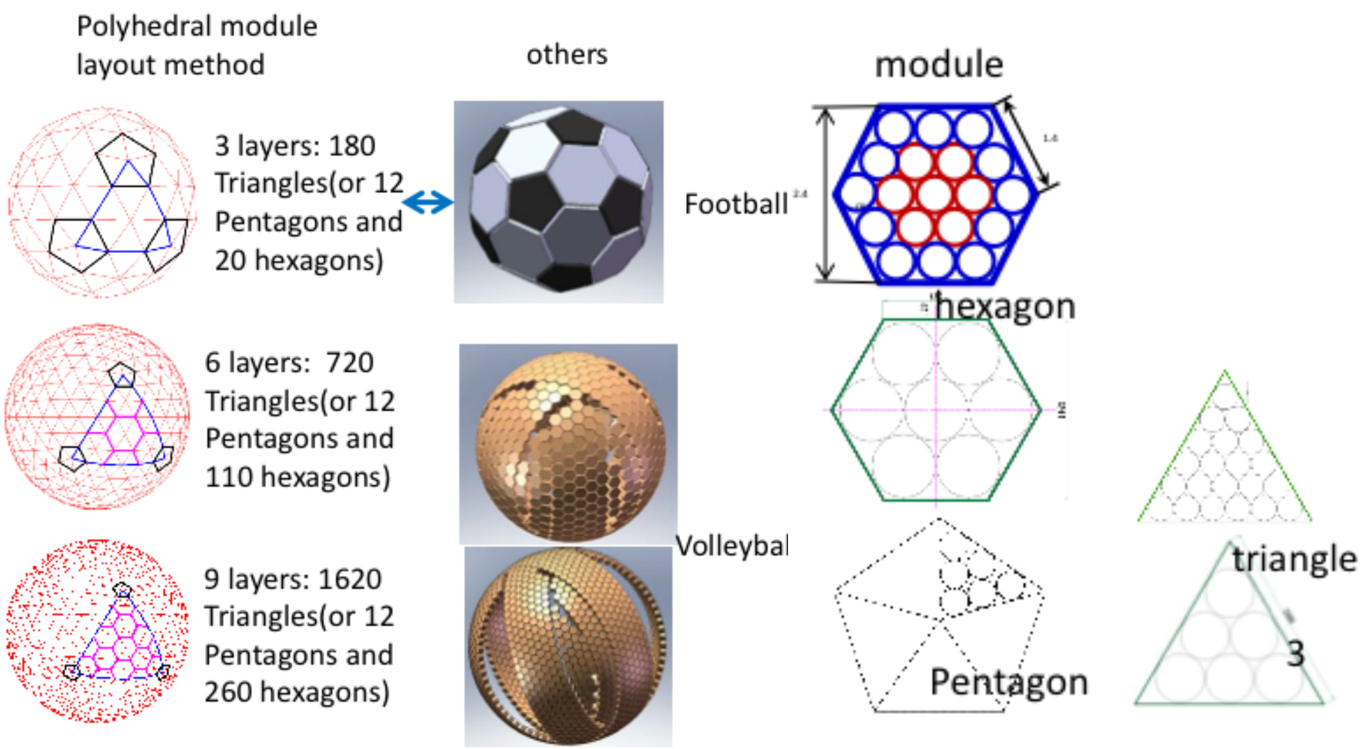
➡ **An unprecedented LS detector is under development for the JUNO project —> a great step in detector technology**

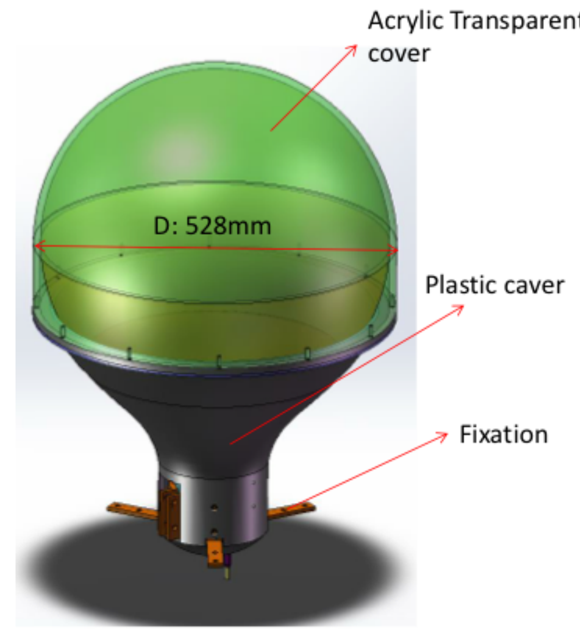
The JUNO Detector Design



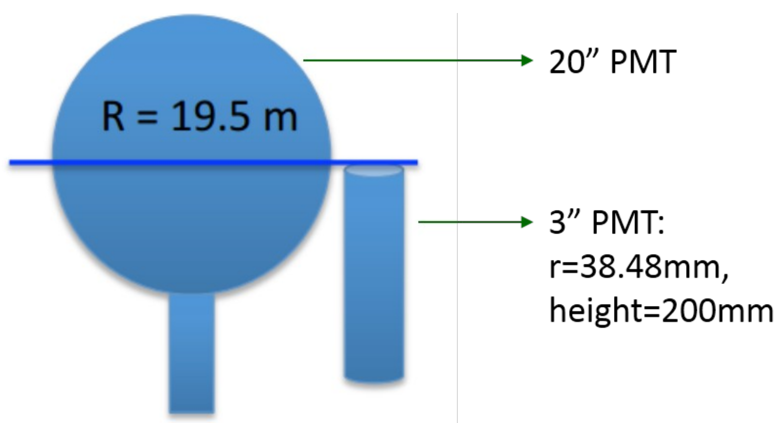
- JUNO central detector design: a 35m diameter acrylic sphere holds the LS
- Stainless truss provides mechanical supports to the acrylic sphere and the PMTs
- Water Cherenkov detector with top tracker functions as the muon veto and reconstruction system
- Underwater electronics is the current baseline

More Light: Photocathode Coverage

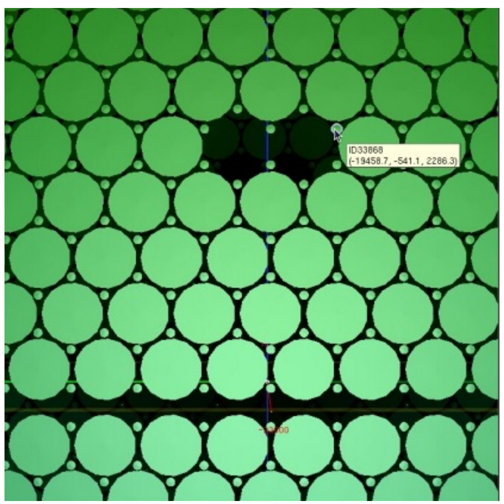




Conceptual explosion proof Structure of PMT



The front end of the 3" PMT is in the same plane as the equatorial plane of 20" PMT

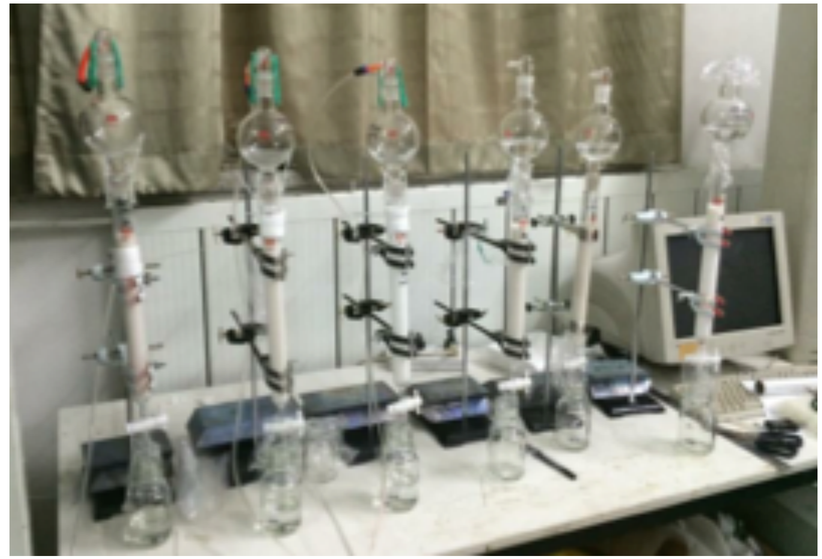


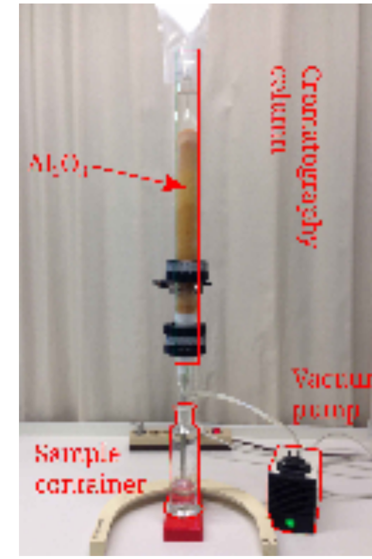
- **Plan A: 20" MCP-PMT**
- **Plan B: 10" Photonis China**
- **Plan C: 20" SBA Hamamatsu**

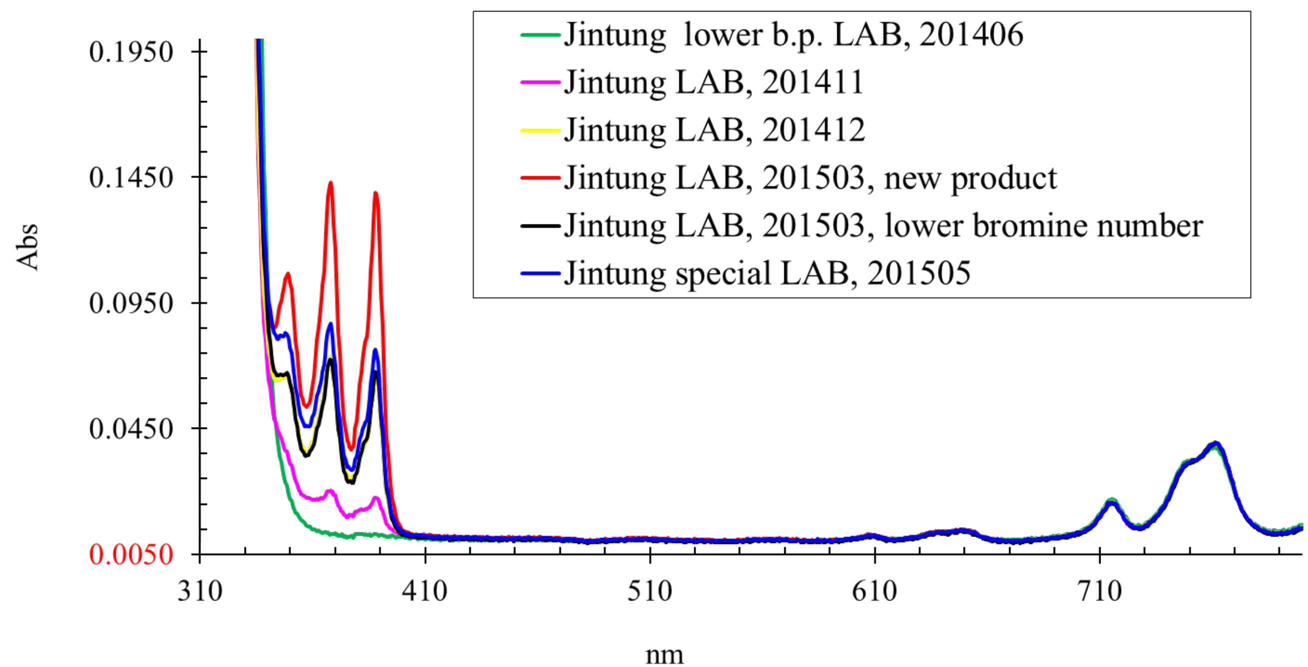
More details on the 3" PMT design in parallel session by Yury Gornushkin

More Light: More Transparent LAB-based Liquid Scintillator

- There are a few key points about liquid scintillator: **light yield, optical transparency and radioactive purity**
  - To improve optical transparency and reduce radioactive impurity, purification is needed
  - Various vendors' samples are being tested, >20m (at 430nm) attenuation lengths achievable in lab with PPO and bis-MSB.
  - Various groups are doing studies. All see space for improvements and R&D activities are ongoing in parallel.



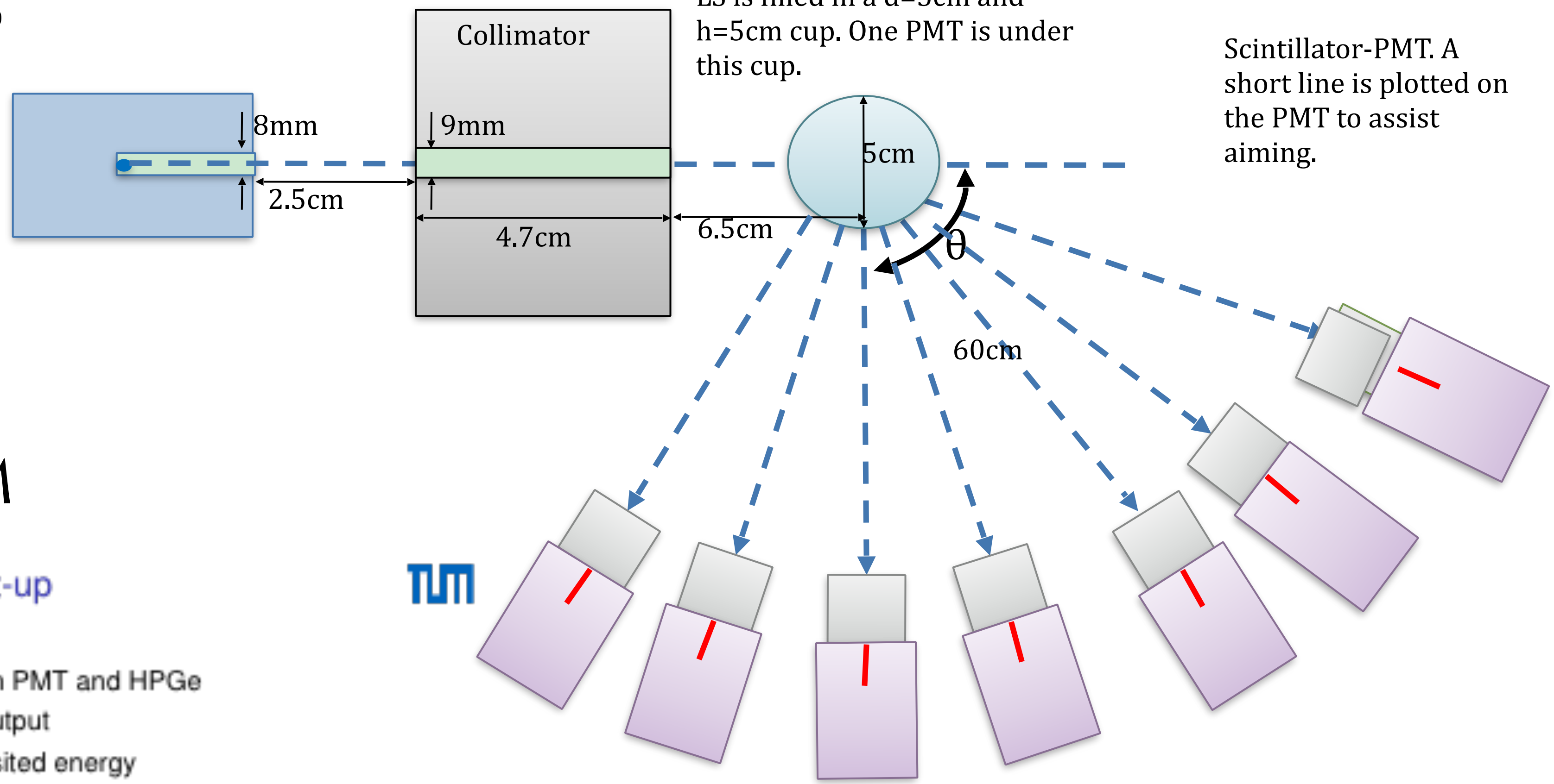




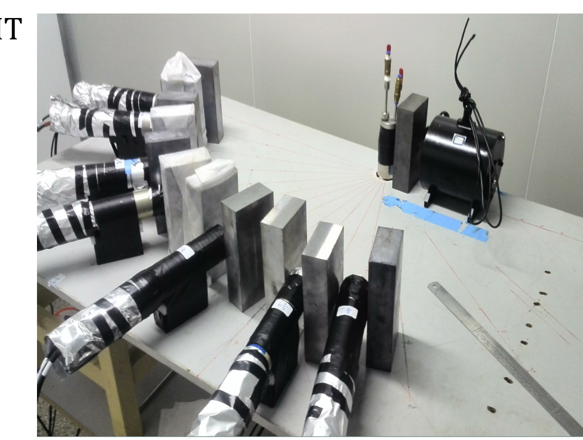
Setup I: IHEP

LS is filled in a d=5cm and h=5cm cup. One PMT is under this cup.

Scintillator-PMT. A short line is plotted on the PMT to assist aiming.



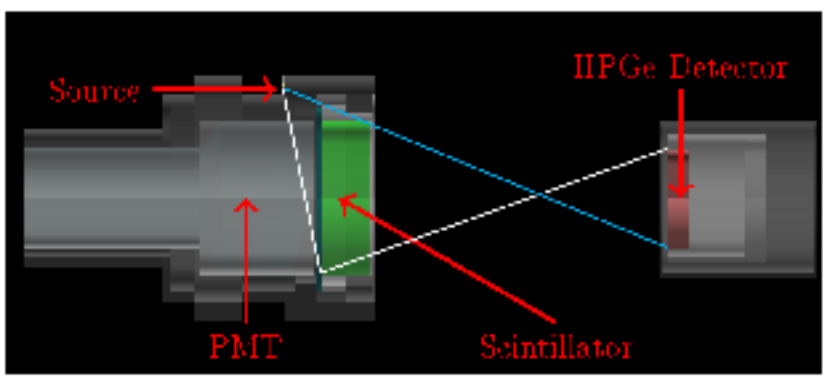
7 LaBr-PMT



Setup II: TUM

Electron quenching: set-up

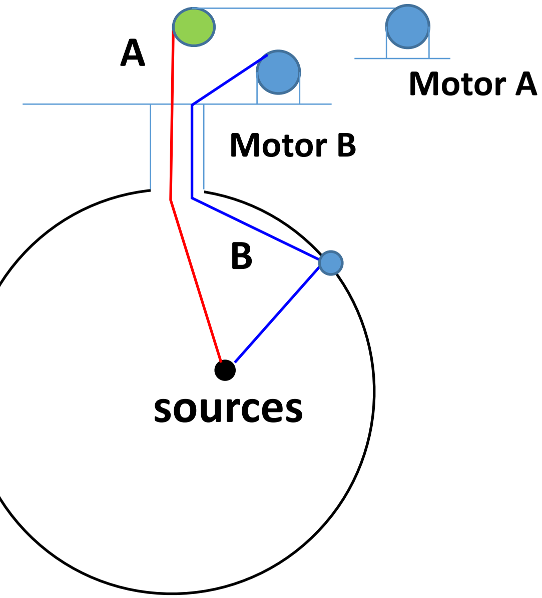
- Conincidence between PMT and HPGe
- PMT signal ⇒ Light output
- HPGe signal ⇒ Deposited energy



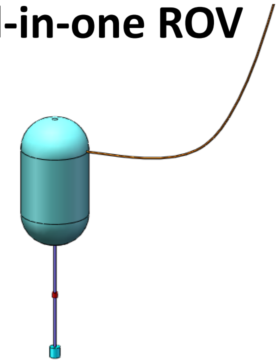
Better Precision: Calibration System Conceptual Designs

- Point radioactive source calibration systems
  - An automatic rope system is the most primary source delivery system
  - A ROV to be more versatile
  - A guide tube system to cover the boundaries and near boundary regions
- A UV laser system being design to calibrate the LS properties in situ
- Also considering short-lived diffusive radioactive sources to calibrate the detector response

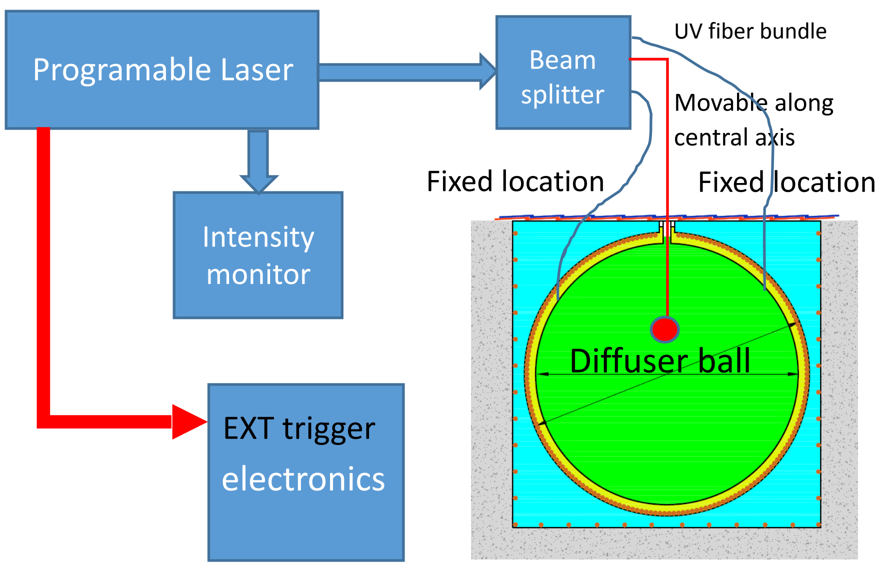
A-B rope synchronous motion



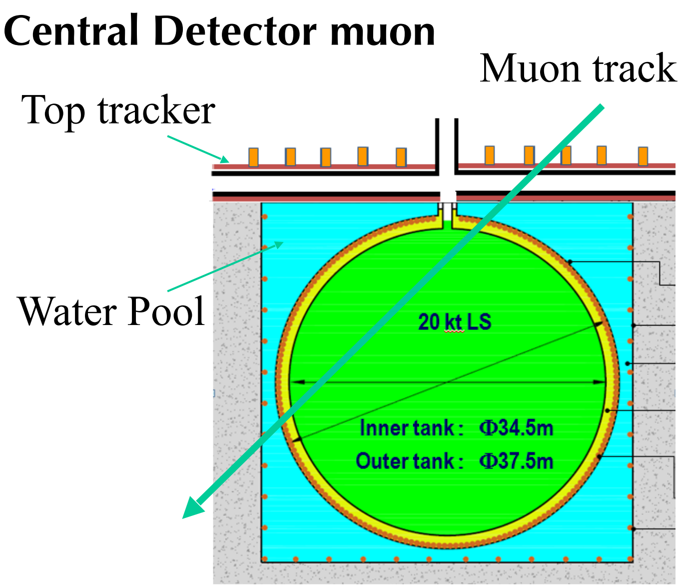
All-in-one ROV

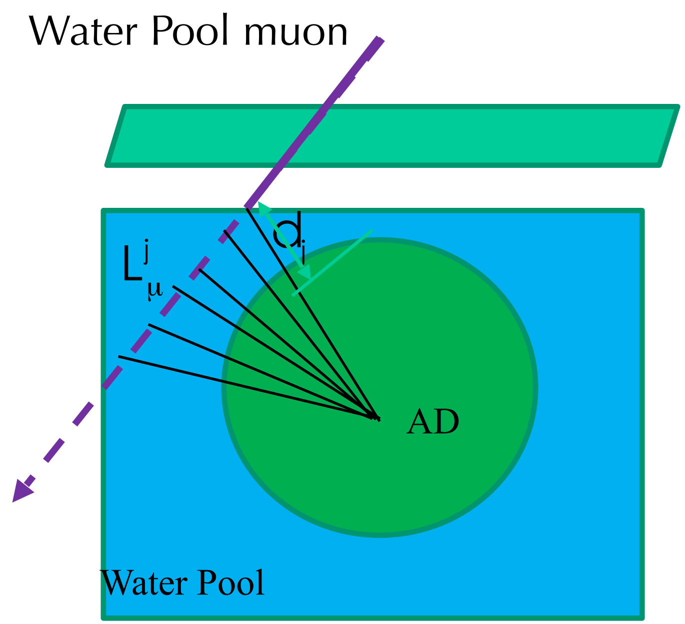


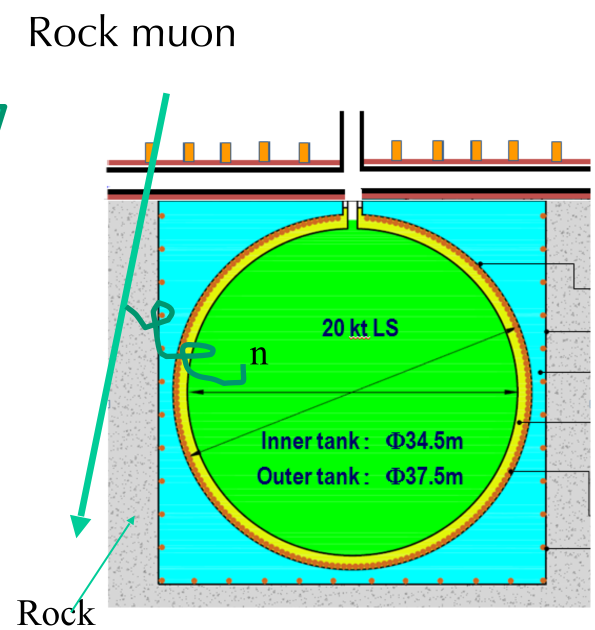
sources



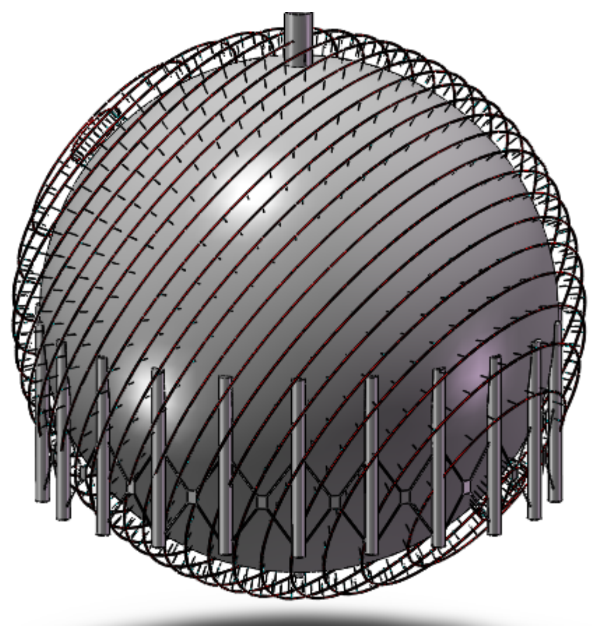
Veto System Considerations and Designs





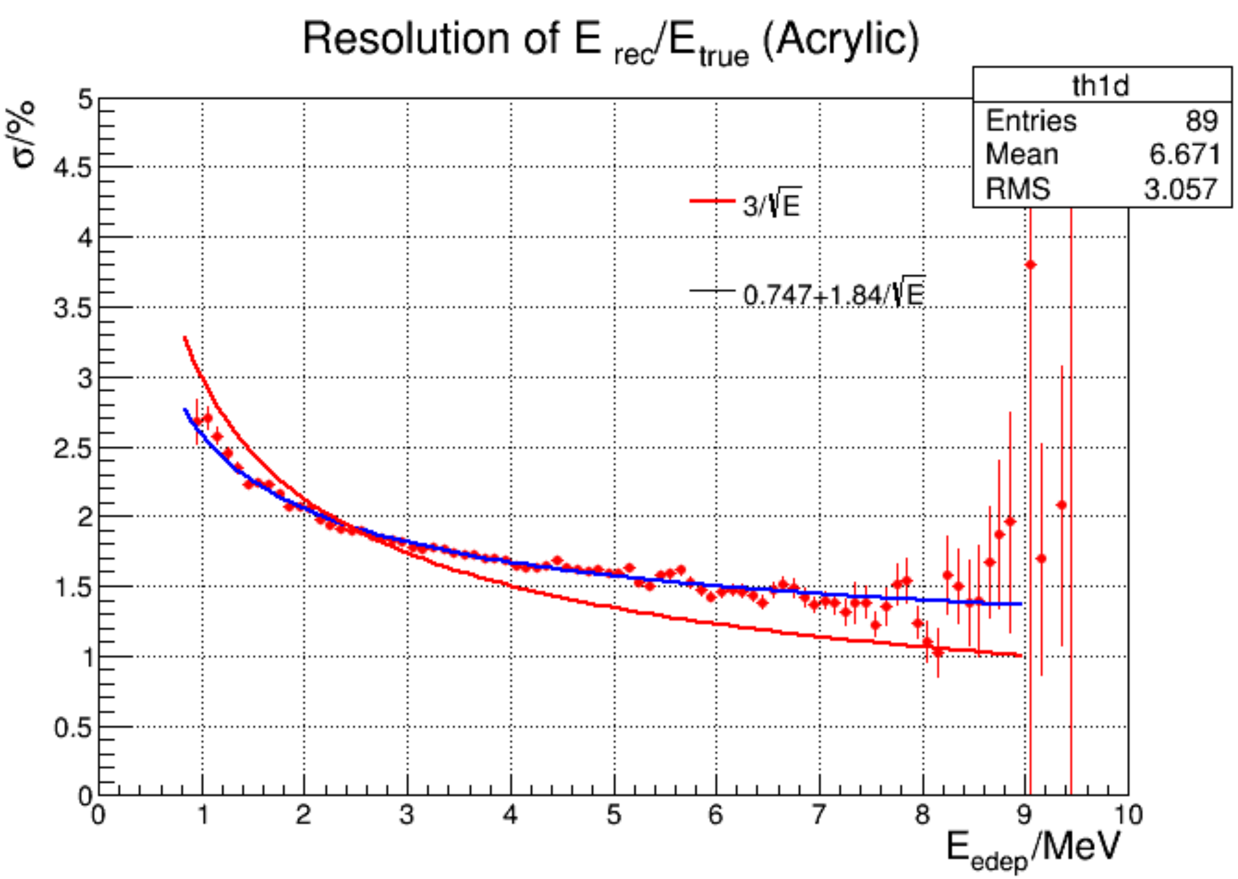


- Veto is not just a veto. Besides radioactive background shielding, we also need tracking information to better understand and remove cosmogenic backgrounds
  - The main body is the water Cherenkov detector
  - OPERA scintillator calorimeters will be moved to JUNO as the Top Tracker (TT)
- Earth magnetic field compensation coils are being designed together with the veto system design
- Radon removal, control and monitoring are under study



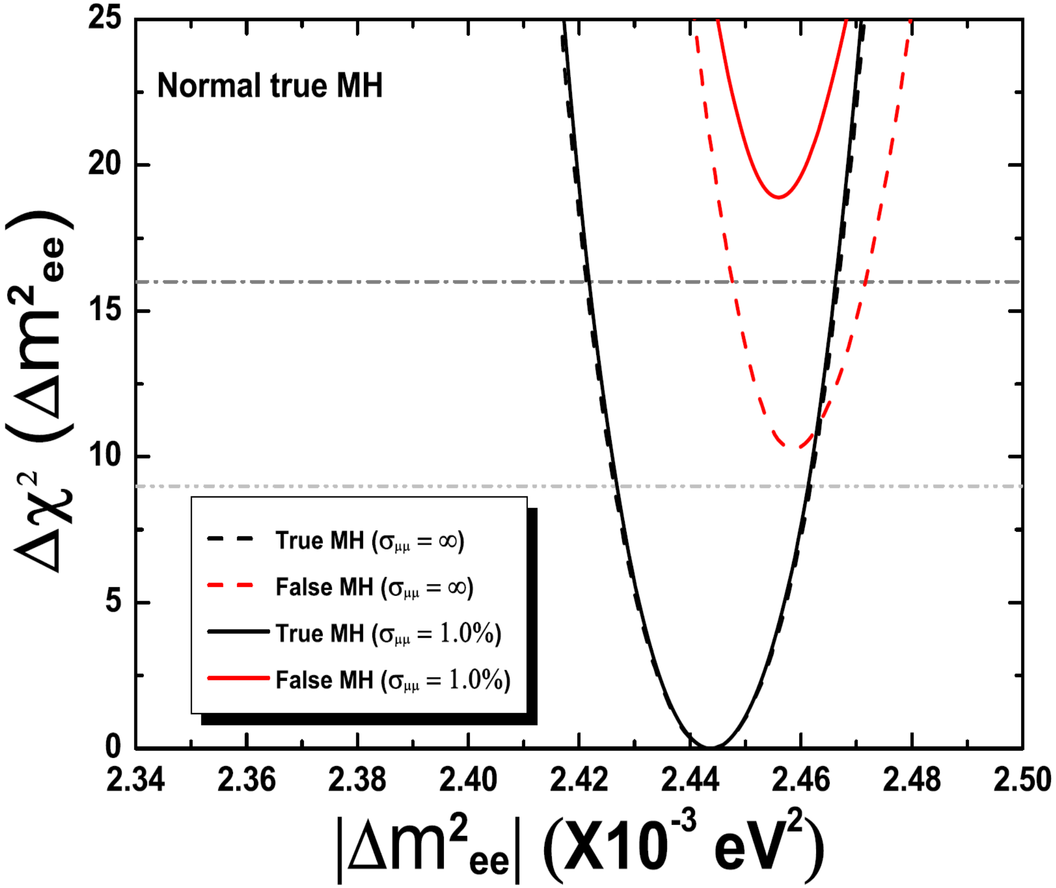
Putting Everything Together (Simulation)

- A framework SNiPER is developed at IHEP for the need of non-collider experiments. Major components of the JUNO central detector are implemented
- Assumptions: PMT QE 35%; LS light yield 10.4k photons/MeV and L_{attn} = 20m @430nm



- Simulation suggests that effective photocathode coverage can reach ~75% after considering the (current) support structures.
- A ~3%/√E energy resolution is plausible based on simulation.

Expected Significance to Mass Hierarchy



- ~3-sigma if only a relative spectral measurement without external atmospheric mass-squared splitting
- ~4-sigma with an external Δm^2 measured to ~1% level in ν_μ beam oscillation experiments
    - ~1% in Δm^2 is reachable based on the combined T2K+NOvA analysis by S.K. Agarwalla, S. Prakash, WW, arXiv: 1312.1477
- *(Side remark: What is the global picture considering the inputs from PINGU and ORCA? NuFACT'16?)*

✓Realistic reactor distributions considered

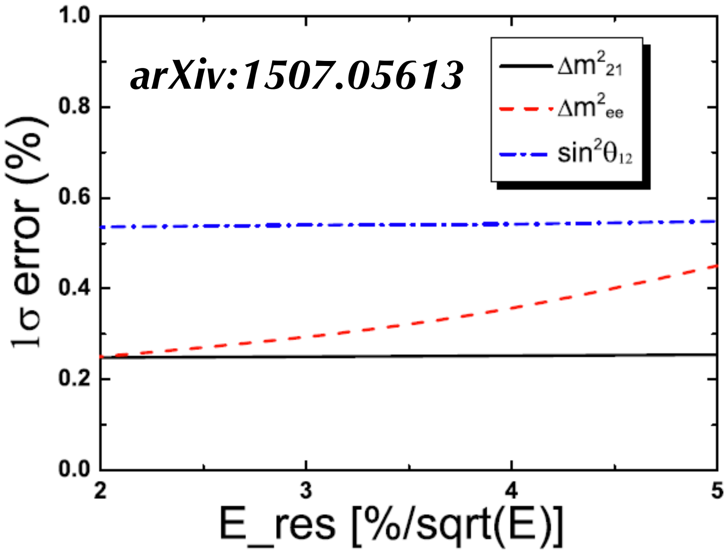
✓20kt valid target mass, 36GW reactor power, 6-year running

✓3% energy resolution and 1% energy scale uncertainty assumed

JUNO Precision Measurements Warranted

Global now
arXiv:1507.05613

	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant Exps.	KamLAND	MINOS	SNO	Daya Bay	SK/T2K
Individual 1σ	2.7% [121]	4.1% [123]	6.7% [109]	6% [122]	14% [124, 125]
Global 1σ	2.6%	2.7%	4.1%	5.0%	11%



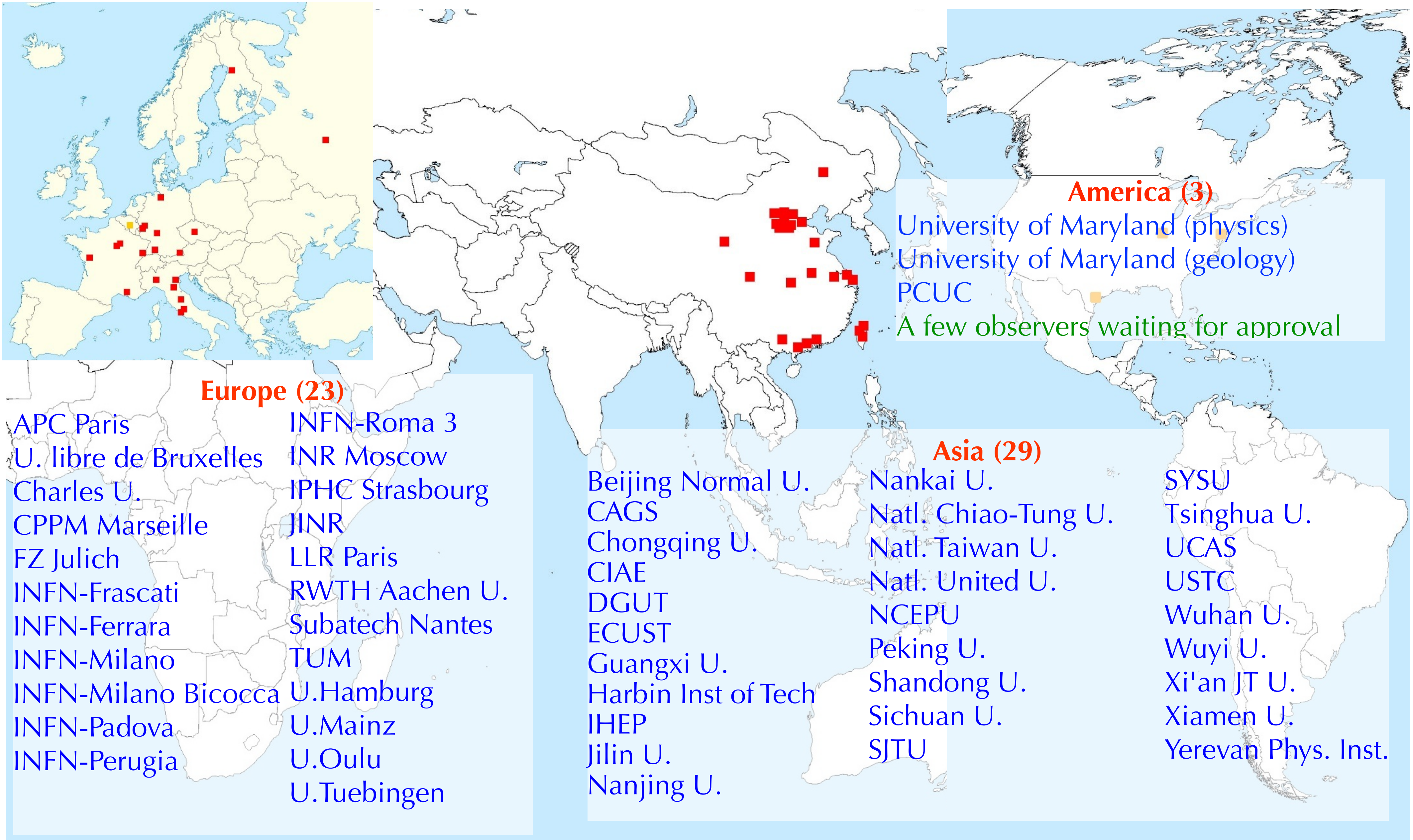
Consistent conclusion from an independent study by A.B. Balantekin et al, Snowmass'13, arXiv:1307.7419

- Precision <1% measurements are warranted in a experiment like JUNO
  - Enable a future ~1% level PMNS unitarity test
  - Neutrinoless double beta decay needs precise θ_{12}

	Nominal	+ B2B (1%)	+ BG	+ EL (1%)	+ NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\lvert\Delta m^2_{ee}\rvert$	0.27%	0.31%	0.31%	0.35%	0.44%

JUNO: 100k evts
arXiv:1507.05613

JUNO Collaboration: 55 Groups from 4 Continents



Europe (23)

- APC Paris
- U. libre de Bruxelles
- Charles U.
- CPPM Marseille
- FZ Julich
- INFN-Frascati
- INFN-Ferrara
- INFN-Milano
- INFN-Milano Bicocca
- INFN-Padova
- INFN-Perugia
- INFN-Roma 3
- INR Moscow
- IPHC Strasbourg
- JINR
- LLR Paris
- RWTH Aachen U.
- Subatech Nantes
- TUM
- U.Hamburg
- U.Mainz
- U.Oulu
- U.Tuebingen

Asia (29)

- Beijing Normal U.
- CAGS
- Chongqing U.
- CIAE
- DGUT
- ECUST
- Guangxi U.
- Harbin Inst of Tech
- IHEP
- Jilin U.
- Nanjing U.
- Nankai U.
- Natl. Chiao-Tung U.
- Natl. Taiwan U.
- Natl. United U.
- NCEPU
- Peking U.
- Shandong U.
- Sichuan U.
- SJTU
- SYSU
- Tsinghua U.
- UCAS
- USTC
- Wuhan U.
- Wuyi U.
- Xi'an JT U.
- Xiamen U.
- Yerevan Phys. Inst.

America (3)

- University of Maryland (physics)
- University of Maryland (geology)
- PCUC
- A few observers waiting for approval

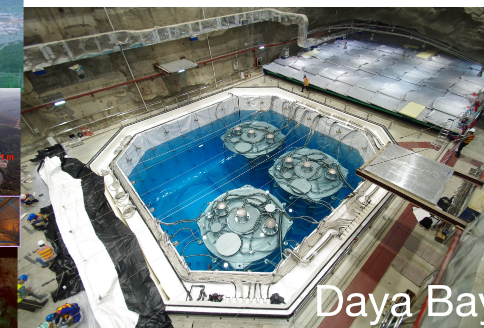
Summary and Conclusion

- **The Daya Bay experiment delivers the most precise theta13 measurement and soon, the atmospheric mass-squared splitting**
- **The value of theta13 has enabled the possibility of resolving neutrino mass hierarchy in medium-baseline reactor neutrino experiments**
- **A medium-baseline reactor neutrino project in China, JUNO, has received approval**
  - **Collaboration** officially formed July 2014; **Ground Breaking** was on Jan 10, 2015; by the end of July 2015, the **civil is progressing well**: slope tunnel >⅓; shaft >⅛; the **central detector structure design** is chosen; the collaboration has expanded to **55 groups on 4 continents** — still accepting new members
  - R&D activities addressing challenges in parallel among collaborators
- **JUNO has great potential in resolving neutrino mass hierarchy, guarantees precision measurements, and offers other rich physics**
- **JUNO plans to start data taking in 2020 — stay tuned!**

Neutrino Physics at Nuclear Reactors and Its Future

Neutrino Mass Hierarchy

courtesy: Karsten Heeger



θ_{13}

2012 - Observation of short-baseline reactor electron antineutrino disappearance

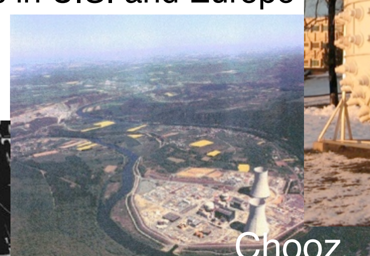
2008 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

1956 - First observation of (anti)neutrinos



Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

KamLAND, Japan
Double Chooz, France
Reno, Korea
Daya Bay, China

JUNO is changing the field: a new level of massive liquid scintillator detector technology!

- Challenges
- Opportunities
- Efforts&Expectations

Time Correlation Detection of Reactor Antineutrinos

Detection Principle: Inverse Beta Decay (IBD)

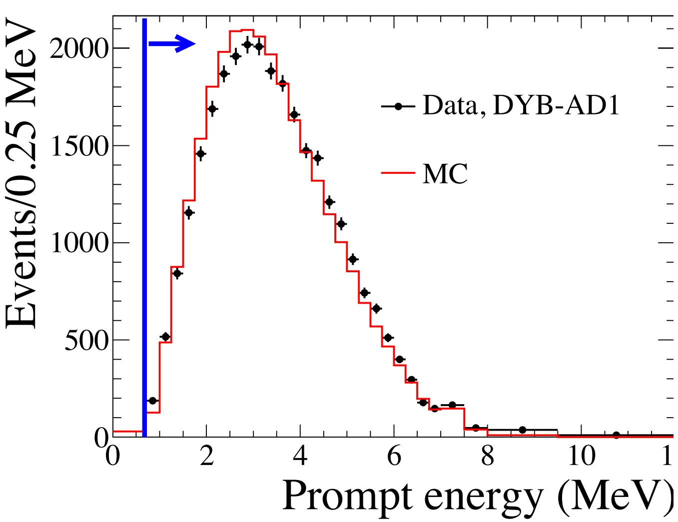
0.1% Gd doped liquid scintillator (LS) as target

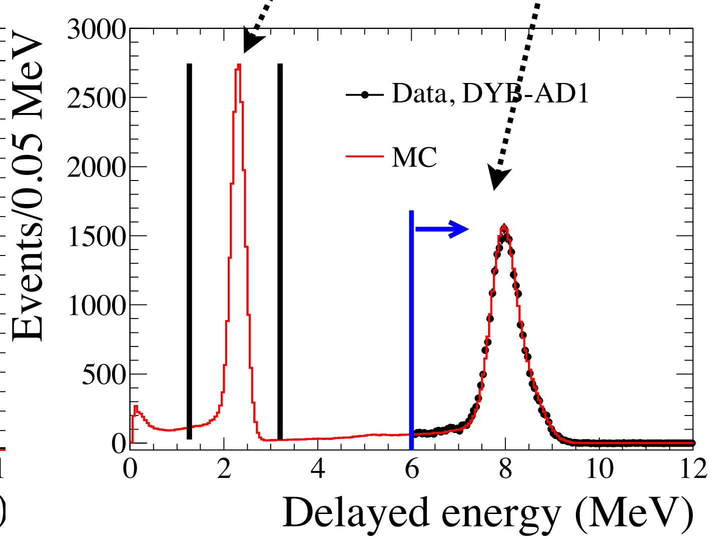
$$\bar{\nu}_e + p \to e^+ + n \xrightarrow{0.3\mathrm{b}} n + p \to D + \gamma(2.2\,\mathrm{MeV})$$

$$n \xrightarrow{\sim 49{,}000\mathrm{b}} n + Gd \to Gd^* \to Gd + \gamma(\sim 8\,\mathrm{MeV})$$

$$E_{\bar{\nu}_e} \approx E_{e^+} + m_n - m_p$$

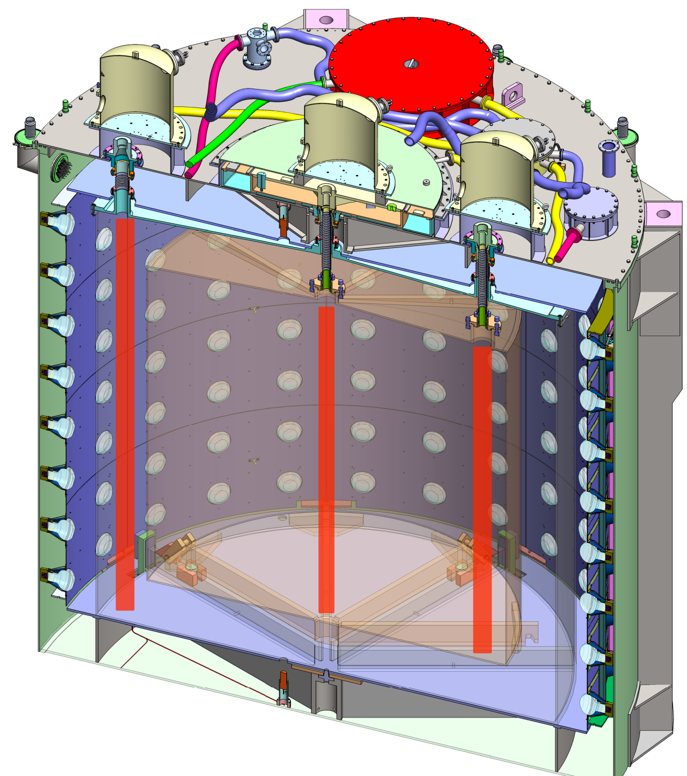
Prompt-delayed correlation is the key!





Correlated Signals

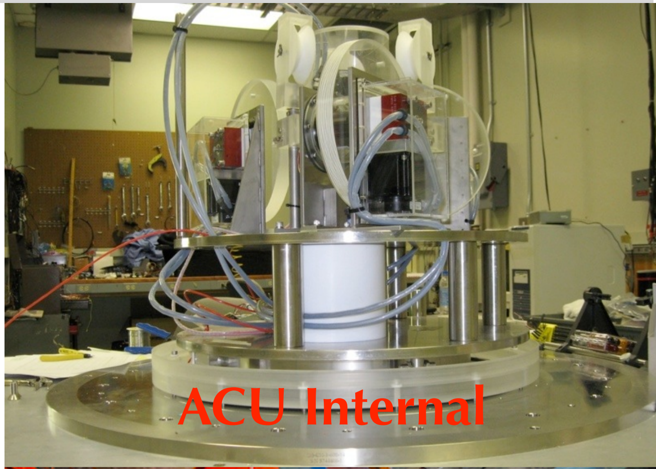
- Powerful background suppression
- Well-defined targets: captures generate lights in LS zones and 8MeV delayed signals only from the Gd zone

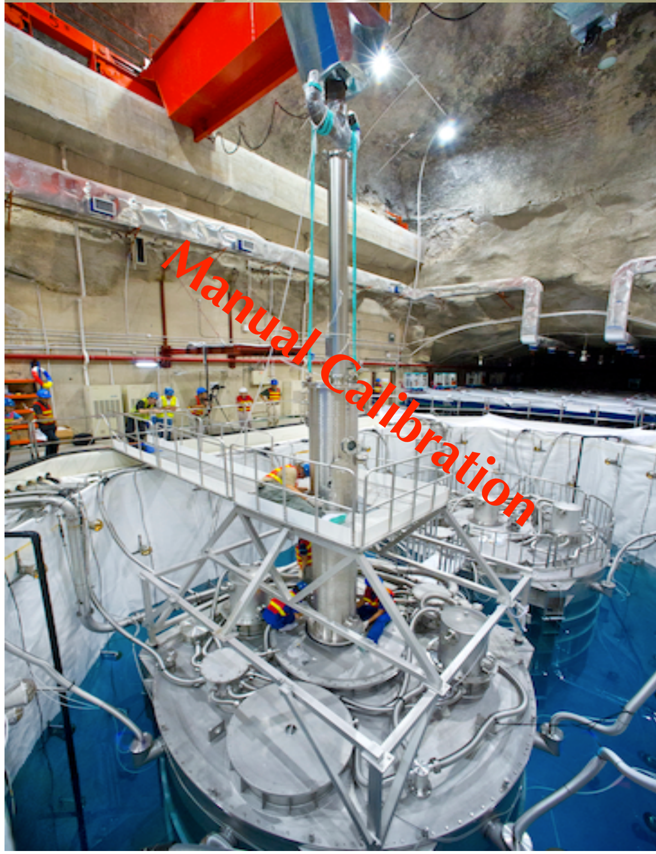


Daya Bay Detector Calibrations

- Three automated calibration units (ACU) on each detector, 2 for the Gd-LS volume and 1 for the LS one, carry out **weekly calibrations** (vertical scans)
  - Sources: ~100Hz ^{68}Ge(e^{+}), ~20Hz ^{60}Co, ~0.7Hz ^{241}Am-^{13}C(n), and a LED diffuser ball
- **Special calibration efforts** in Summer 2012
  - Manual calibration system (MCS) with 4π scan was installed to further understand detector energy responses using Pu-C and Co sources
  - One detector's ACUs were loaded with ^{137}Cs, ^{54}Mo, ^{40}K, Pu-C, and ^{241}Am-Be sources and thorough scanned vertically
  - A stronger ^{241}Am-^{13}C is placed on a detector to understand the induced background better

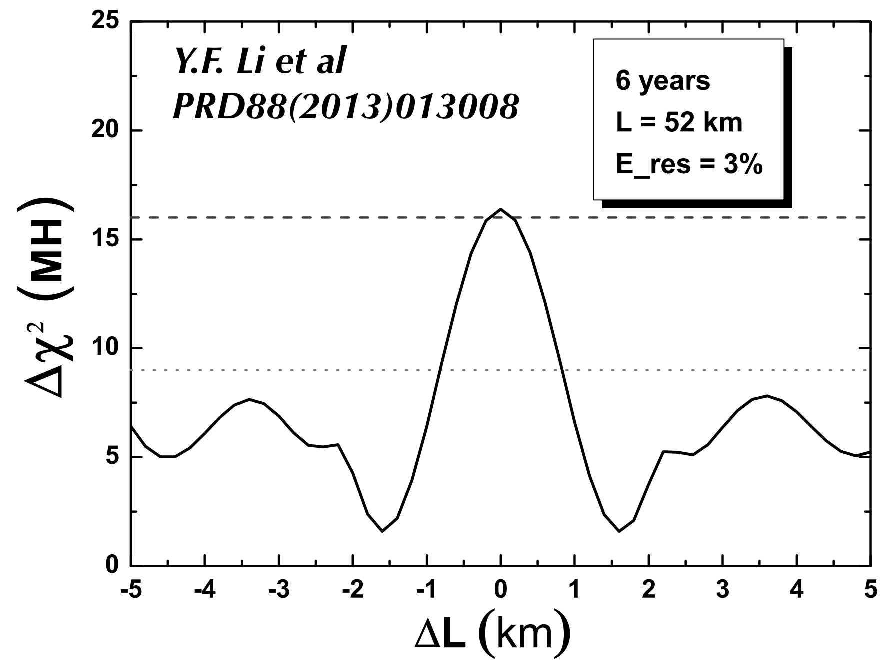
✓**The Daya Bay absolute energy scale uncertainty has reached ~1%, and the relative energy scale ~0.2%, after a thorough analysis of the collected calibration data**



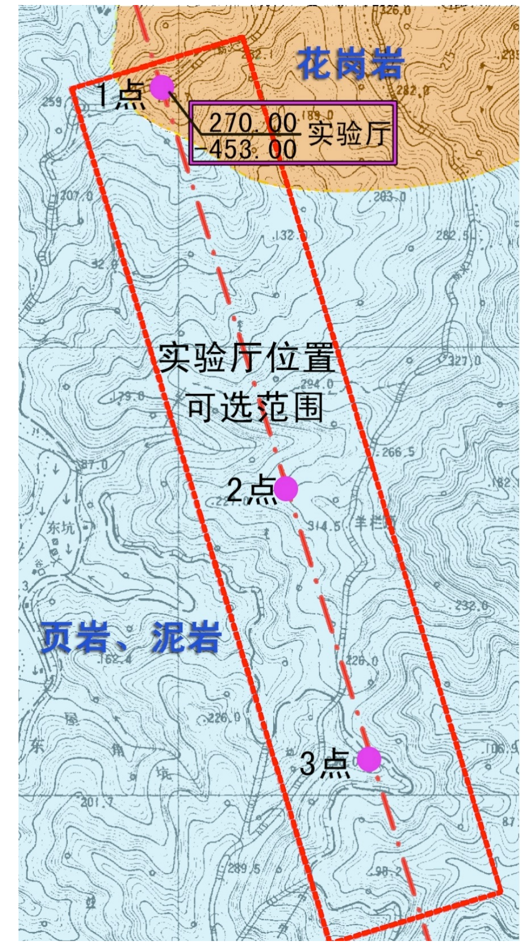


A Subtlety in Designing the Baselines

- MH information is in the small oscillation waggles driven by the atmospheric mass-squared splittings whose oscillation length is ~2km for reactor spectrum



- Reactor cores at the same power plant like to be ~km apart. If baselines are shifted by half oscillation length, they cancel each other's signals.



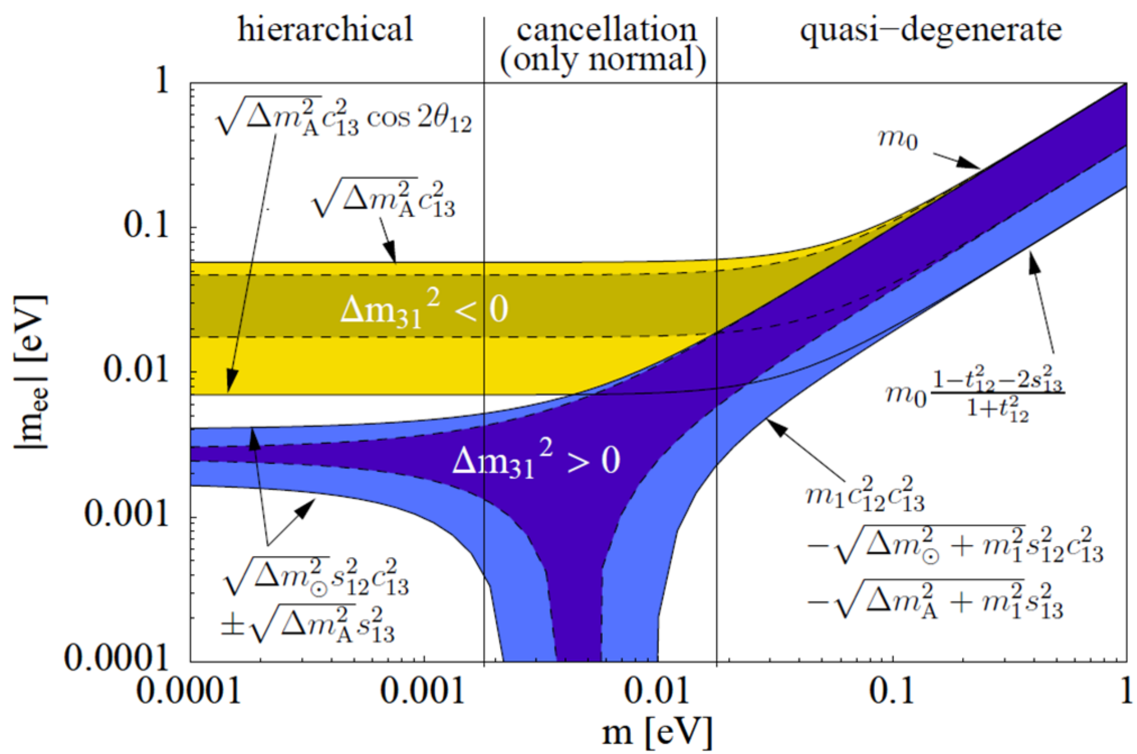
Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline(km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline(km)	52.76	52.63	52.32	52.20	215	265

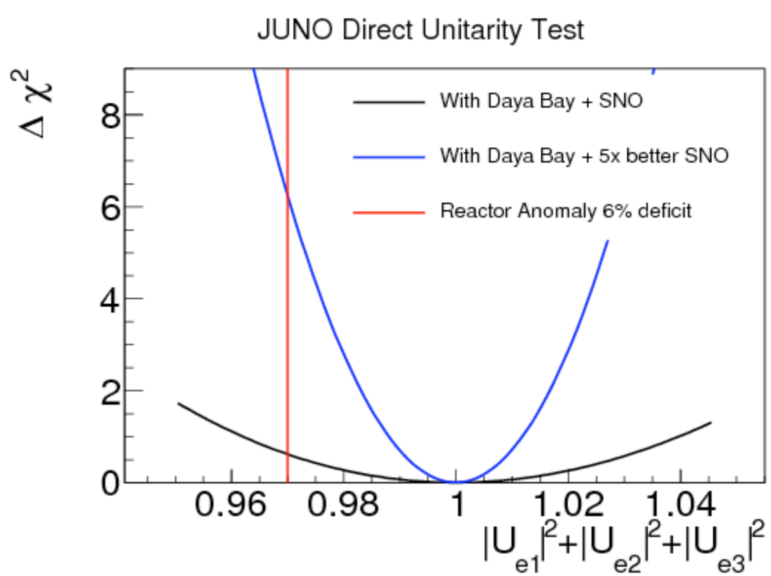
- The JUNO design has considered this issue and made sure baseline differences are less than 0.5km

JUNO Impact of Precision Measurements

- Three-neutrino paradigm test
- Valuable input to the neutrinoless double beta decay experiments.

W. Rodejohann, J. Phys. G **39**, 124008 (2012)





Qian, X. et al. arXiv:1308.5700

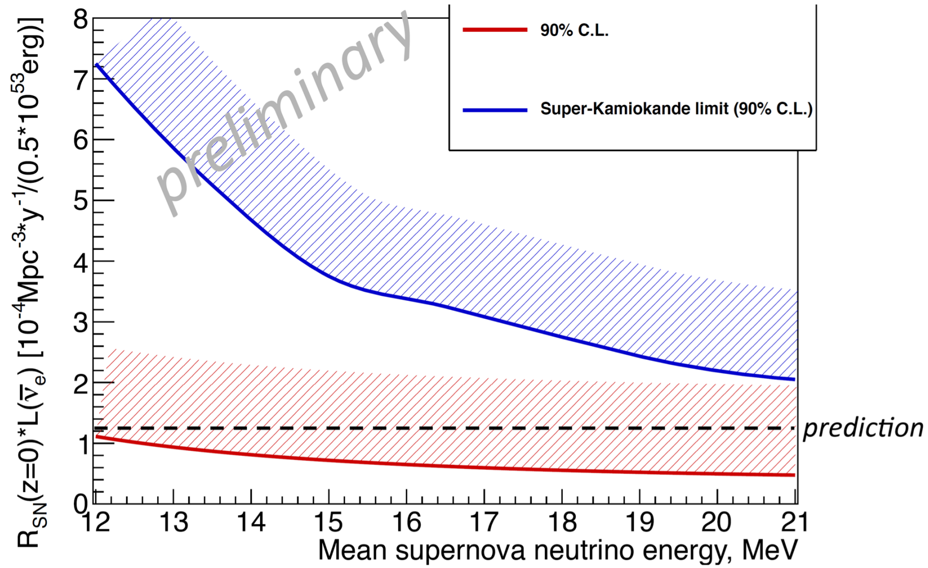
Direct unitarity test of $|U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2=1$ by combining JUNO, Daya Bay, and solar results. We considered two scenarios i) current SNO constraint and ii) a five times better constraint than SNO.

Other Physics Potential of JUNO

- Supernova neutrinos
- Diffused supernova neutrinos
- Proton decay $P \rightarrow K^+ + \bar{\nu}$

  $\tau > 1.9 \times 10^{34}$ yr (90% C.L.)
- Geoneutrinos
  - KamLAND: 30±7 TNU [PRD 88 (2013) 033001]
  - BOREXINO: 38.8±12.0 TNU [PLB 722 (2013) 295]
  - JUNO (preliminarily projected): 37±10%(stat)±10%(syst)TNU

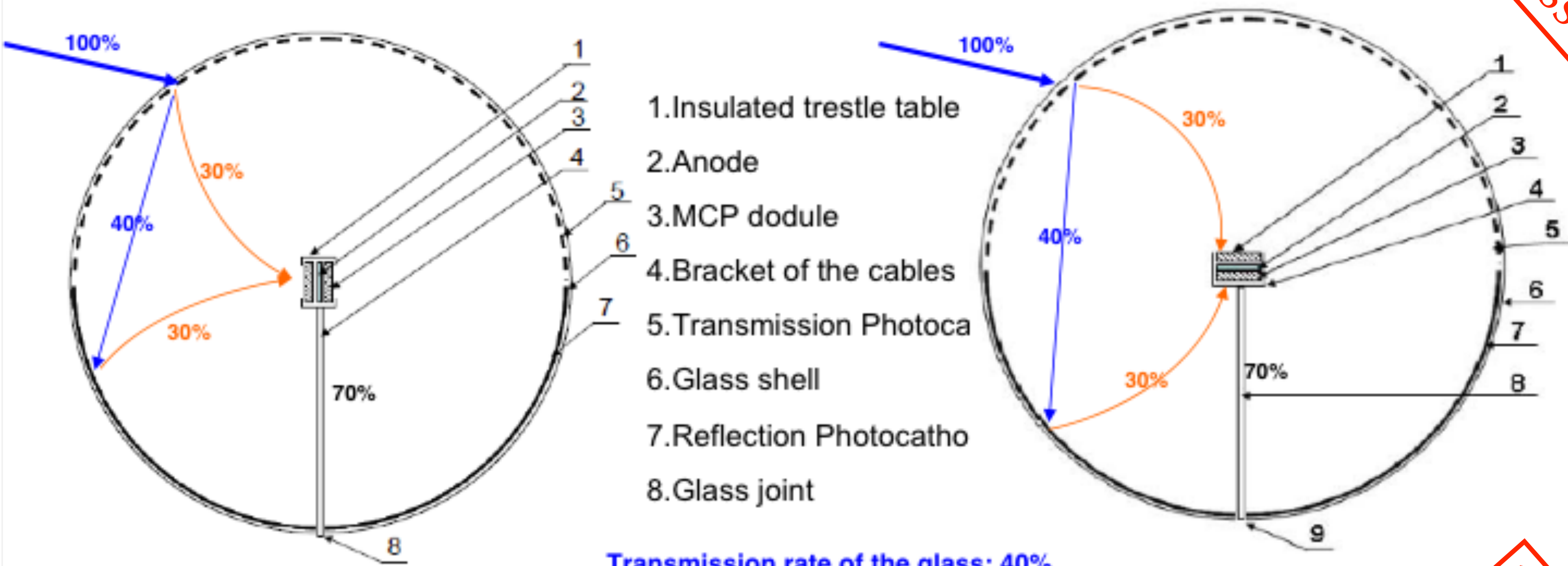
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	NC	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\text{C} \rightarrow \nu + {}^{12}\text{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\text{C} \rightarrow e^- + {}^{12}\text{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\text{C} \rightarrow e^+ + {}^{12}\text{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2



- Solar neutrinos: high demand on the radioactive background purity. Challenging and BOREXINO is the standard.
- Atmospheric neutrinos: not much value in redoing what Super-K has done. With JUNO's good energy resolution, atmospheric neutrinos could potentially aid the MH case (PINGU type signal)
- ……

More Light: New Types of PMTs

1) Using two sets of Microchannel plates (MCPs) to replace the dynode chain
2) Using transmission photocathode (front hemisphere) and reflection photocathode (back hemisphere) } Fully active sphere surface



Transmission rate of the glass: 40%

Quantum Efficiency (QE) : of Transmission Photocathode 30% ; of Reflection Photocathode 30% ;

Collection Efficiency (CE) of MCP : 70%;

If nothing else changes, the detection efficiency (QE*CE) is nearly doubled by "saving" the ~40% transmitted photons.

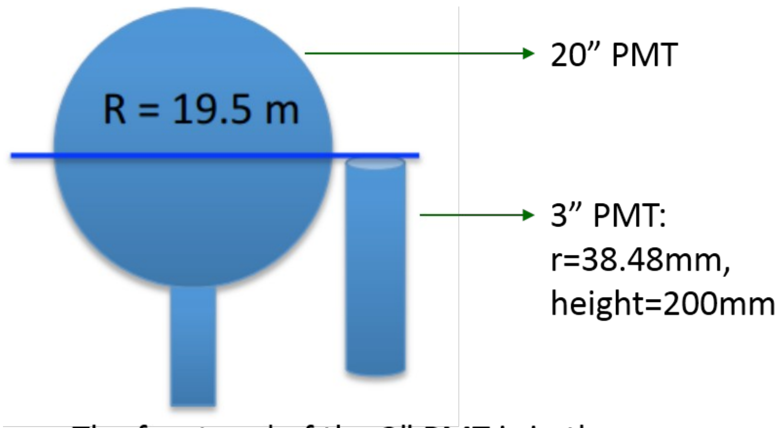
JUNO PMT Plan A progressing well

- JUNO PMT plan B: Photonis China PMTs
- JUNO PMT plan C: new 20" Hamamatsu SBA high QE PMTs

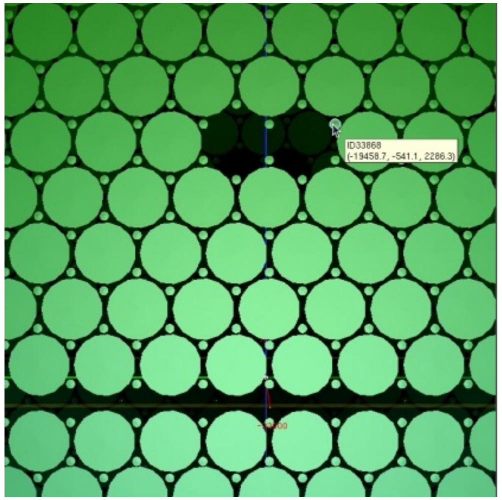
3 Plans in Parallel by Collaborators

Even Better: A Double Calorimetry Design

- Small PMTs (sPMT) are cheaper and faster in time response (<1ns), lower noise and higher QExCE
- Adding 3″ PMTs in the gaps: ~2 SPMTs for every large PMT (LPMT)
  - increase the photocathode coverage by ~1%
  - improve the central detector muon reconstruction resolution
  - avoid high rate supernova neutrino pile-up (if very near)
  - increase the dynamic range and global trigger
- An approved proposal by the collaboration (currently allocating resources)



The front end of the 3" PMT is in the same plane as the equatorial plane of 20" PMT



Complementary Roles by sPMTs and LPMTS